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A SURVEY OF THE CURRENT STATE-OF-THE-ART IN  
HIGH-ENERGY-PRODUCT PERMANENT MAGNETS

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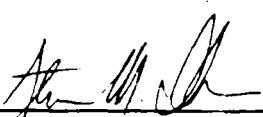
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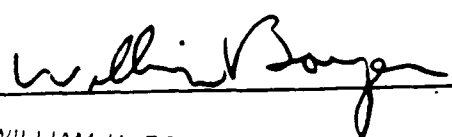
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<p>The current state-of-the-art of high energy permanent magnets (HEPM, with (BH max) &gt; 10MGOe) was surveyed to inform design engineers about presently available magnetic material types. Users of HEPM's were asked to provide information about their current and future requirements on the properties of permanent magnets for their devices. The responses were divided into six application categories, and are presented in the form of "specifications". An up-to-date list of HEPM manufacturers, their addresses, and a summary of the materials they make is included, and cross-referenced. A functioning prototype fixture was built to perform demagnetization curve testing at temperature between -197 and +300°C. Design considerations are discussed. Example demagnetization curve sets as functions of temperature were measured and are presented.</p>					
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## 1.0. Introduction

Permanent magnets (PM's) are a key component in many of today's electrical/electronic devices and subsystems, in both the industrial and military arenas. Military applications include aircraft/aerospace vehicle control surface actuators; airborne power systems; inertial guidance/stabilization systems; and millimeter and microwave power tubes for communications, fire control and ECM.

The push in all of these areas is for higher performance in smaller packages; additionally, devices are being used in ever harsher environments, most notably at extremes of heat and cold, in chemically aggressive atmospheres, and sometimes in the presence of energetic radiation. Under those conditions, even the "best" PM materials can fail to deliver the required performance. The needed quantitative information on magnetic properties and stability under such conditions is still largely unavailable.

## 1.1. Objectives

This project involved several objectives which included: Identify the operating conditions and environmental ranges for different permanent magnet application areas; define PM property requirements for these areas; collect data for existing PM materials, especially at the extremes of temperature; point out any information gaps; and evaluate the suitability or shortcomings of specific PM materials for different uses.

Information was gathered about the magnetic characteristics which are now, and may soon be, required of HEPM's. The information was obtained from many sources including a review of the current engineering literature about device and machine applications of PMs and new designs that are under consideration, and from discussions with design engineers. The result is several sets of HEPM "specifications", based on specific existing and anticipated device applications, and with a view toward present and future magnetic materials needs.

To assess what is currently available, commercial product literature was solicited from all known U.S. manufacturers of high-energy permanent magnet (HEPM) materials, and from some selected foreign companies. Those high energy materials that could be used in demanding applications are listed in this report along with published properties, brand names and their manufacturers.

This report also includes a discussion of the current state of the production technology and of R&D activities aimed at HEPM's, with emphasis on elevated temperature behavior. In cases where existing materials already meet one or more of the "specifications", the magnets are identified and described.

## 1.2. Organization of the Information in this Report

Section 1.0 describes the overall objectives of this project and explains how the information is organized.

Section 2.0 discusses the nature of the information that had to be collected under this contract and explains the techniques that were used to obtain it. There were two basic avenues which had to be addressed. Input was solicited from PM users about the properties they require of their magnets and the conditions under which the magnets must operate. This was assembled into "specifications" for various categories of applications. Also, current information was gathered about what kinds of HEPM materials are being offered by magnet manufacturers and the properties of those materials.

Section 3.0 contains a comprehensive review of the types of HEPM's currently available from domestic and foreign magnet manufacturers. It discusses the physical and magnetic properties that HEPM manufacturers can offer today, and attempts to identify areas that require more research and development. In addition, a list of manufacturers (and their sales offices where appropriate) is given in Appendix I.

The target specifications presented in Section 4.0 of this report identify those combinations of magnetic and physical properties which are important to engineers and designers in various application areas. This information was compiled from responses to a survey that was distributed, and from information obtained through discussions with design and applications engineers. Included are current and near-future applications and magnet property requirements.

Section 5.0 includes observations of trends and specific points of interest that came out of the survey compilation. Shortcomings of present magnets are discussed, and an overview is presented of research efforts that are under way to address some of the limitations. Prospects for improved magnetic properties and/or completely new PM materials are considered.

Section 6.0 describes a new magnetic test fixture, developed under this contract, which can be used to measure demagnetization curves on HEPM materials over a wide temperature range. Some curve sets that were measured with the new fixture are shown, with data tables.

## 2.0. Methodology

One of the main goals of this project was to draw up specifications which identify the magnetic properties and, especially, the high/low temperature behavior required at the present time for important classes of military/space and commercial devices or machines. To accomplish this it was necessary to identify the most demanding applications, and use them to determine a list of characteristics that magnets must have under the required operating conditions to be most useful. Some of this could be done on the basis of our prior experience, and more by reading recent technical publications. The most fruitful method, however, involved



contacting device designers who work for manufacturers of the devices, and obtaining information about the permanent magnet uses in, and requirements for, their designs. We then endeavored to translate the mostly device-oriented engineering design parameters that were given into materials-oriented specifications of magnet properties.

## 2.1. Determining Specifications for Magnets needed for Different Applications

Unfortunately, the design of any magnetic circuit, especially one involving PM's, is a complex process. There are many characteristics of the PM material that enter into the device's performance. Physical characteristics like differential thermal expansion, brittleness, tendency to crack under stress, and thermal conductivity must be considered when placing the magnet and fastening it to its final location. Static magnetic properties like ease of magnetizing, resistance to demagnetization (due to elevated temperature exposure while curing a glue bond, or due to handling of the magnet), and magnetic interaction with other components must be considered when planning for the assembly of the device. And then, after the mechanics of building the device are established, the dynamic magnetic performance as a function of time and temperature during operation and storage must be evaluated.

Obviously the engineer must know a great deal of information about PM materials and magnetic circuits before he begins to design a new device that incorporates PM's. Of the many characteristics that are important, only a relative handful can be meaningfully quantified in terms of simple numbers or figures of merit. As the engineering of any complex product involves a sort of art in pulling together many interacting factors, so does the incorporation of a PM material in a device. Thus the "specifications" given in this report tend to be in the form of essays rather than lists of numbers.

Even the technical description of any one characteristic of a magnet usually involves stating the behavior of that characteristic under different operating conditions. Clearly this makes it difficult even to write a thorough PM product description as a stand-alone item, much less to come up with a standardized presentation so that different material types can be readily compared. Despite the difficulties, some method of presentation and comparison is required, and there is presently no standardized approach. This report attempts to state PM requirements for several classes of demanding HEP applications based on the input from PM users, and to describe available magnetic materials in a format that lends itself to making comparisons.

The first part of this task, the statement of requirements, was approached in several ways. A list of six broad, general PM application areas was made. That list was then expanded to include specific manufacturers and research laboratories which make or develop devices that fit within the general categories. A survey/questionnaire was assembled and sent to a variety of organizations and individuals, a list

of whom appears in Appendix II. The full text of the survey appears at the end of this report as Appendix III.

The survey recipients were selected based on their expertise in a particular application area. Using leading questions and explanations, the survey attempted to elicit responses in a somewhat standardized form so that they could be compared, analyzed and compiled into a meaningful and coherent overview of current PM requirements in demanding applications. So as not to overly restrict the answers, respondents were encouraged to comment on areas of concern to them, which may not have been specifically or adequately covered in the main body of the survey, and to ignore questions that do not pertain to the respondent's application.

Seventeen replies were received, out of thirty-nine organizations and individuals to whom the survey was sent. Wherever possible, the transmittal of the survey itself was preceded by a telephone call to the specific individual who would be in the best position to provide a meaningful response. The project and its goals were explained in some detail, and the individual was asked to make a commitment to respond to the questionnaire. Those who made verbal commitments honored them in almost all cases. About two months after the initial distribution, which was accomplished by mail and facsimile machine, letters of reminder were sent to those who had not replied to the first request. This effort brought in a few additional responses.

With the information gleaned from the survey responses, a target specification was drawn up for each of the six general application areas. Each target specification focusses on those characteristics of the PM material which were identified as being critical to the application. The format for these specifications represents an effort to standardize the presentation and allow for easy comparison. The format attempts to identify comprehensively all the categories of properties of PM materials which might be of interest for any application. The individual target specifications of Section 4.0 show data entered only in those parts of the format which apply to the category in question.

## 2.2. Information about Commercial Magnet Materials

The task of describing available HEPM materials involved collecting the raw information from many sources and then presenting it in a format that allows comparison with the requirements. Requests for current product literature were sent to most of the US magnet manufacturers of which KJSA has knowledge (including some makers of low energy PM materials only), and some foreign producers. The latter were selected from among the companies known to produce high-performance rare earth-cobalt or RE-iron based magnets. Selection criteria were: the perceived suitability of their products for the applications considered here; whether the companies actively market in the USA; and finally whether we had personal contacts with individuals there who were expected to be co-operative and helpful.

Table I lists some of the identifying characteristics and physical properties that should be included with the specifications for every commercial magnet material. Except for simple values of remanence, coercivity, knee field and maximum static energy product, the magnetic properties defy easy tabulation. Temperature dependence of various properties is complex and nonlinear. Engineers like to speak of temperature coefficients, but these involve many potential pitfalls. One must know exactly what property was measured, and how. There are various ways of defining temperature coefficients and it is important to specify which definition was used. The temperature coefficient of a property can be defined at a specific temperature, or over a specified temperature range. By choosing the temperature range carefully, the temperature dependent behavior of a given property can often be made to look substantially better than it really is. A detailed discussion of temperature coefficients goes far beyond the scope of this report. It is important, however, to be aware that temperature coefficients are a frequent target of "specmanship", i.e. they are often massaged to yield good looking numbers on paper. The only correct way to evaluate the suitability of a magnet material for a particular application is to consider the actual plots of various key magnetic properties as a function of temperature. These must be supplied by the manufacturer for each type of material.

Table I. Identifiers and important physical properties that should appear on PM specification sheets.

## IDENTIFICATION

Manufacturer and Brand Name:

Generic Magnetic Material Type: (RECo, REFe)

Specific Compositional Type: (SmCo<sub>5</sub>, Sm<sub>2</sub>Co<sub>17</sub>, Sm<sub>2</sub>(Co,Fe,Cu)<sub>17</sub>, Nd<sub>2</sub>Fe<sub>14</sub>B, etc.)

Product Type: Sintered, hot-deformed, polymer bonded, etc.

## PHYSICAL PROPERTIES

(If anisotropic, this should be stated and multiple values given.)

Mass density.....  
 Mechanical Hardness.....  
 Poisson's Ratio.....  
 Yield strength.....  
 Electrical resistivity/conductivity..  
 Specific Heat.....  
 Thermal conductivity.....  
 Coefficient of thermal expansion.....

### 3.0. Review of Available HEPM Materials and Information Offered by Magnet Manufacturers

For the purposes of this review, we have defined "High Energy Permanent Magnets" (HEPM) as magnets having a static energy product,  $BH_{\max} \geq 10$  MGOe. There are several classes of permanent magnet materials which offer high remanence, high coercivity and high energy product. They are, in order from most recently developed to oldest: Nd-Fe-B,  $Sm_2Co_{17}$  and  $SmCo_5$  (the so-called rare earth permanent magnets, or REPM). There are other new types of PM materials under development whose laboratory record energy products exceed 10MGOe, but these high energy levels are not available in production magnets. Among older magnet types, some AlNiCo varieties have also been developed to have  $BH_{\max}$  levels slightly in excess of 10 MGOe in laboratory samples. The best production magnets (AlNiCo 9), however, have only 8-9 MGOe, and all AlNiCo grades have low coercive force values by today's standards, in the range of 500-2000 Oersteds.

The only other magnet material that marginally fits our definition of a HEPM is platinum-cobalt. Here, too, the best laboratory samples reached 11-12 MGOe; commercial magnets have 7-9 MGOe. The coercivity of Pt-Co is adequately high for most purposes (6-7 kOe). The principal - and fatal! - drawbacks of this material are its poor availability and extremely high raw material price: it contains 78 weight percent platinum. While it had some uses in military microwave tubes and inertial guidance devices before Sm-Co was developed, Pt-Co is now restricted to some medical implants and a few uses in accelerometers and similar precision devices. Even these could be redesigned around REPM's. Some data are listed for AlNiCo 9 and Pt-Co for comparison purposes, but the focus is almost exclusively on rare-earth type materials.

Table II lists salient properties and general magnetic information about the classes of HEPM materials considered in this report.

Of the three main REPM/HEPM types, Nd-Fe-B (Neo) is the newest and is receiving the most attention. "Neo" is available in two basic forms: The first is produced by standard powder metallurgical methods consisting of alloy preparation, grinding into fine powder, pressing into a compact (aligned or isotropic) and then sintering to high density. The second form results from a rapid solidification process, where the alloy is induction melted and sprayed onto a rapidly rotating wheel which causes it to cool rapidly and solidify in an almost amorphous form. The resulting flaky material (the so-called "amorphous ribbon") is magnetically isotropic and can be combined with various binders to produce bonded magnets with energy products of up to about 10MGOe. By further processing of the flakes (without a binder) using an additional hot-pressing step, isotropic magnets with about 13 MGOe can be made. By following this up with hot deformation (e.g. a die-upsetting step), an anisotropic magnet with energy product of up to about 40MGOe (50MGOe in the laboratory) can be made.

Neo's biggest attraction at present is that the raw material base for this material is significantly larger than that for Sm-Co magnets. This also is interpreted as indicating the potential for lower cost. Thus Neo

(Numbers are approximate. Compositional and property variations in each family can be very extensive.)

COMPOSITIONAL FAMILIES, STRUCTURE TYPES AND BASIC MAGNET PROCESSING METHODS	d [ $\frac{g}{cm^3}$ ]	T <sub>c</sub> [°C]	B <sub>r</sub> AT ROOM TEMPERATURE [kG]	M <sub>Hc</sub> [kOe]	(BH) <sub>m</sub> [MGOe]	TEMP. COEFFICIENT RT → 100°C [%/°C] of B <sub>r</sub> of M <sub>Hc</sub>		MAX. USE TEMPERAT. [°C]	MIN. FIELD TO CHARGE [kOe]
Sm(Ce,Pr)-Co(Fe,Cu) "1-5" SINTERED	7.7- 8.4	500- 750	5- 10.3	5- >25	6- 26	-.045 ↓ -.09	-.2 ↓ -.44	200- 250	15- 20
Sm(Ce,Nd,Y)-Co,Fe,Cu,Zr(Hf,Ti) "2-17" SINTERED	8.3- 8.6	780- 850	9.5- 12	6- >25	20- 31	-.03 ↓ -.06	-.2 ↓ -.4	300- 350	10- 40
Nd(Dy)-Fe-B SINTERED HOT-PRESSED, ISOTROPIC "2-14-1" HOT-DEFORMED, ANISOTR.	~7.4	~310	11-12.5 8-9 10-12	10-24 15-17 12-14	25-40 12-14 22-32	-.12 ↓ to -.13	-.70 -5 -.63	80-120 150 100	~20 ~45 ~25
Nd(Dy)-Fe,Co-B SINTERED	~7.4	300- 500	12- 12.4	8- 18	32- 36	-.07	-.55	150- 160	15- 20
Nd-Fe(Co)-B-Ga SINTERED "2-14-1" HOT-DEFORMED, ANISO.	~7.4	300- 500	10-12.7 11-12.2	10-20 18-20	23-36 28-35	-.09	-.53	140- 160	~20 ~25
Pr-Fe-Cu-B HOT-ROLLED, ANISO. "2-14-1"	~7.4	~300	10.8- 12.6	10- 11.2	27- 30	-.11	-.60	~90	~20

Table II. Magnetic properties of dense REPM  
in or near commercial production in 1989.

could be widely introduced in large scale applications that would completely use up the rare earth-cobalt raw material supply. Although Neo has excellent magnetic properties at room temperature, it has a very low Curie temperature  $T_c$  (around 325°C) and all of its key magnetic parameters have large temperature coefficients. This has so far limited Neo to near-room temperature applications.

The chemical stability of Neo is also very poor so that surface oxidation and subsequent deterioration of the magnet body are a major problem. Although plating and painting of the magnet surface are commonly used techniques for corrosion protection, they are expensive and the results are often less than satisfactory. There are extensive development efforts under way, mostly in Japan, to overcome these limitations by raising the  $T_c$ , improving the chemical stability, and stabilizing the temperature dependent behavior of the remanence and coercivity with metallurgical alloying modifications.

One recent development at Seiko-Epson Corporation in Japan warrants particularly close attention. The company is introducing a Pr-Fe-Cu-B magnet, produced by hot-rolling. This material is claimed to have high energy product and excellent chemical stability. Seiko-Epson claims there are no corrosion problems with this material. The Hot-rolling should help keep processing costs low. Requests for samples, both to contacts at the Seiko-Epson research laboratory and to their U.S. marketing representative, were refused so it was not yet possible to test this potentially very interesting material in the KJSA Laboratory.

For stable operation in extreme temperature environments,  $\text{Sm}_2\text{TM}_{17}$  remains the material of choice.  $\text{Sm}_2\text{TM}_{17}$  magnets resist surface oxidation and magnetic aging, and can provide room temperature energy products of up to about 28MGOe.

$\text{SmCo}_5$  in sintered form behaves very similarly to  $\text{Sm}_2\text{TM}_{17}$ , but is limited to about 22MGOe energy product. In applications where high intrinsic coercivity is required, this is sometimes the best choice of material, although the newer 2-17 magnets also boast very high intrinsic coercivities.

Table III presents a listing of presently available PM products indexed by manufacturer, and Table IV presents a similar list indexed by material type. The information includes names of manufacturers, brand names, and ranges of properties claimed by the manufacturers in their product literature.

#### 4.0. Permanent Magnet Specifications for Selected Application Areas

The responses to the survey discussed above were used to define material properties of interest for various categories of applications. KJS Associates applied its experience in the field of permanent magnets to establish a list of broad applications areas, as shown in Table V. (The categorization is, of course, somewhat arbitrary; there is unavoidable overlap, especially among the machinery subgroups, A-1, A-2 and A-3.)

Table III. Overview of high-energy magnet products ( $BH_{max} > 10 \text{ MGOe}$ ) of Manufacturers who responded to the requests for commercial literature. (Compiled from literature submitted; may be incomplete.)

Manufacturer's Name	Material Type	Brand Names	Type Designation	(BH) <sub>max</sub> [MGOe]
Aimants Ugimag SA (Pechiney, France)	Sintered Sm-Co	RECOMA	20,25,28,28LM	18-28
	Polymer bonded Sm-Co		10(anisotropic)	(9)-10
	T.C., Sint'd. SM-HRE-Co		STAB-0,-0.02	(9)-15
	Sint'd Nd(Dy)-Fe-B	REFEMA	27H,30H,30,35	25-35
The Arnold Engineering Company (SPS Technologies)	Cast Alnico	ALNICO	9	10.5
	Sint'd. R-Co, Nd-Fe-B	(under development)	?	?
Crucible Magnetics	Sint'd Alnico	ALNICO	9	10.5
	Sint'd Sm-Co	CRUCORE	16,18,20,22	16-22
	Sint'd Nd(Dy)-Fe-B	CRUMAX	6 grades (261, 282,301,315, 322,355)	26-35
Electron Energy Corp. (see also Thomas and Skinner)	Sint'd Sm-Co	REMCO	18	18-28
	T.C., sint'd Sm-HRE-Co			(8)-15
	Sint'd Nd-Fe-B	NEO	27,31,35	27-35
	Nd-Dy-Fe-B		27H,30H,33H	27-33
Hitachi Magnetics Corp. (USA)	Sint'd SmCo5	HICOREX	90A,B; 96A,B	16-21.5
	Sint'd Sm2TM17		99A,B	21.5-24
	T.C., sint'd Sm-HRE-Co		92,93	(9)-12
	Sint'd Nd(Dy)-Fe-B	HICOREX-ND	H-94,H-97	23-36
Hitachi Metals, Ltd. (Japan)	Sint'd SmCo5	HICOREX	18A,B; 22A, 24A,26A	15-27
	Sint'd Sm2TM17		23B,H;25B,30	18-31
	T.C., sint'd Sm-HRE-Co		H-13S	10-14
Hoeganaes Corp.	Sint'd Nd(Dy)-Fe-B	ANCORMAG-NEO	6 grades (2620, 2917,2920,3013, 3317,3513)	26-35
IG Technologies, Inc.	Sint'd SmCo5	INCOR	6,18,21	(6)-21
	Sint'd Sm2TM17		22HE,23HB,24HE, 26HE,30HB	22-30
	Polymer bonded Sm2TM17		7-P1	(7)
	Sint'd Nd(Dy)-Fe-B	NEIGT	15 grades	27-40
	Polymer bonded Nd-Fe-B		7,10,14 PB	(7)-14
Krupp Widia (W.Germany)	Sint'd SmCo5	KOERMAX		15-21.5
	Sint'd Sm2TM17			18-27.5
	Sint'd Nd-Fe-B	KOERDYM		25-40

Table III. (continued)

Manufacturer's Name	Material Type	Brand Names	Type Designation	(BH)max [MGOe]
Magnequench (Delco-Remy, GMC)	R/Q, Nd-Fe-B Polymer bonded Hot pressed Hot deformed	MAGNEQUENCH	MQ-1A,B MQ-2 MQ-3	(8.7-9.5) 13.7 28-45
Namiki Precision Jewel Co., Ltd. (Japan)	Sint'd Sm <sub>2</sub> TM17	NAMINET	4 grades (KM-20,23, 26,30)	18-31
Ovonix Synthetic Materials Co.	R/Q, Nd-Fe-B Plastic bonded	HIREM (under development)	18,18HC	10.8-11.4
Phillips/Mullard (Netherlands, UK)	Sint'd Sm-Co Sint'd Nd-Fe-B Sint'd Nd-Dy-Fe-B	RES	190 270,300,350 255,275,305	18 27-35 25-30
Recoma, Inc. (Ugimag-USA)	Sintered Sm-Co Polymer bonded Sm-Co T.C., Sint. SM-HRE-Co Sint'd Nd(Dy)-Fe-B	RECOMA  REFEMA	20,25,28,28LM 10(anisotropic) STAB-0,-0.02 27H,30H,30,35	18-28 (9)-10 (9)-15 25-35
Seiko Epson Ltd. (Japan)	Polymer bonded Sm <sub>2</sub> TM17 Compression molded Injection molded Polymer bonded Nd-Fe-B (R/Q-3) Compression molded Injection molded	SAM SAMLET  NEOM NEOLET	11,13,15,17 3,5,7,8,9,10  8,10	8-17 (2.2)-10.5  (6)-10 (4)-(4.7)
Shin-Etsu Chemical Company, Ltd.	Sint'd RE(Co,Cu) <sub>5</sub> Sint'd RE <sub>2</sub> TM17 T.C., sint. RE-HRE-Co Sint'd Nd(Dy)-Fe-B	SEREM-R  SEREM-N	7 grades 8 grades A,B 6 grades	(2.5)-8.5-17 (4)-16-24 16-17.5 23-40
Sumitomo Special Metals Co., Ltd. (Japan)	Sm-Co-based Sint'd Nd(Dy)-Fe(Co)-B	CORMAX NEOMAX	1300, 1800, 2000, 3000 10 grades	10-25 25-40
Swift Levick Magnets Ltd. (UK)	Sint'd SmCo <sub>5</sub> Sint'd Sm <sub>2</sub> TM17 Polymer bonded Sm-Co Sint'd Nd(Dy)-Fe-B	SUPERMAGLOY  NEOMAGLOY	S1,S2 S3 B2,B3 N28,35,28H	15-22 25-30 (6-8) 25-35
TDK Electronics Company, Ltd. (Japan)	Sint'd SmCo <sub>5</sub> Sint'd Sm <sub>2</sub> TM17	REC	14,16,18,20 22,24,26,30	12-21 20-31



Table III. (continued)

Manufacturer's Name	Material Type	Brand Names	Type Designation	(BH)max [MGOe]
Thomas & Skinner, Inc. (see also EEC)	Cast Alnico	AL	9,9Nb	10.5-11.8
	Sint'd Nd-Fe-B	NEO	27,31,35	27-35
	Sint'd Nd-Dy-Fe-B		27H,30H,33H	27-33
Thyssen Edelstahlwerke A.G. (W. Germany)	Sint'd SmCo5	SECOLIT	155,170,180	18-22.5
	Sint'd Sm2TM17		215	25-28
	Sint'd Nd(Dy)-Fe-B	NERONIT	240,270	30-35
Ugimag Recoma AG (Switzerland)	Sintered Sm-Co	RECOMA	20,25,28,28LM	18-28
	Polymer bonded Sm-Co		10(anisotropic)	(9)-10
	T.C., Sint. SM-HRE-Co		STAB-0,-0.02	(9)-15
	Sint'd Nd(Dy)-Fe-B	REFEMA	27H,30H,30,35	25-35
Vacuumschmelze Hanau (W. Germany)	Sint'd SmCo5	VACOMAX	145,170,200	17-26
	Sint'd Sm2TM17		165,225	19-30
	T.C., sint'd Sm-HRE-Co		80T,95T	(8.8)-14
	Polymer bonded Sm-Co		65K	(7.5)-10
	Sint'd Nd(Dy)-Fe-B		8 grades	21-42
	Platinum-Cobalt			(9)-10

Key: T.C. = "temperature compensated"

HRE = "heavy rare earth"

Sint'd = "sintered"

R/Q = "rapidly quenched"

Table IV. Commercial source list of the different types of high-energy magnets (from manufacturers' survey responses).

Material Types	Producer's Names	Product Brand Names
A. Sintered Sm-Co-based (1-5 and 2-17 structural types.)	Aimants Ugimag S.A. Crucible Magnetics, Inc. Electron Energy Corp. Hitachi Magnetics Corp. (USA) Hitachi Metals, Ltd. (Japan) IG Technologies, Inc. Krupp Widia Magnettechnik Namiki Precision Jewel Co., Ltd. Phillips/Mullard Recoma, Inc. Shin-Etsu Chem. Co., Ltd. Sumitomo Special Metals Company Swift Levick Magnets, Ltd. TDK Electronics Co., Ltd. Thyssen Edelstahlwerke AG Ugimag Recoma AG Vacuumschmelze Hanau	RECOMA CRUCORE REMCO HICOREX HICOREX INCOR KOERMAX NAMINET RES RECOMA SEREM-R CORMAX SUPERMAGLOY REC SECOLIT RECOMA VACOMAX
B. Temperature- Compensated Sintered Sm-Hf-Co (1-5 and 2-17 structural types).	Aimants Ugimag SA Electron Energy Corporation Hitachi Magnetics Corp. (USA) Hitachi Metals, Ltd. (Japan) Recoma, Inc. Shin-Etsu Chemical Company, Ltd. Ugimag Recoma AG Vacuumschmelze Hanau	
C. Sintered Nd(Dy)-Fe-B (2-14-1 structural type).	Aimants Ugimag SA The Arnold Engineering Co. Crucible Magnetics Electron Energy Corporation Hitachi Magnetics Corp. (USA) Hoeganaes Corp. IG Technologies, Inc. Krupp Widia Phillips/Mullard Recoma, Inc. Shin-Etsu Chemical Company, Ltd. Sumitomo Special Metals Co., Ltd. Swift Levick Magnets, Ltd. Thomas & Skinner, Inc. Thyssen Edelstahlwerke AG Ugimag Recoma AG Vacuumschmelze Hanau	REFEMA (under develop.) CRUMAX NEO HICOREX-ND ANCORMAG-NEO NEIGT KOERDYM  REFEMA SEREM-N NEOMAX NEOMAGLOY NEO NERONIT REFEMA

Table IV. (continued)

Material Types	Producer's Names	Product Brand Names
D. R/G-Hot pressed or hot deformed, Nd(Dy)-Fe-B based.	Magnequench Ovonic Synthetic Materials Co.  Seiko Epson, Ltd.	MAGNEQUENCH HIREM (under develop.) NEOM, NEOLET
E. Polymer-bonded Sm-Co or Nd-Fe-B (1-5, 2-17, 2-14-1 structural types).	Aimants Ugimag SA IG Technologies, Inc. Magnequench Ovonic Synthetic Materials Co. Recoma, Inc. Seiko Epson, Ltd.  Swift Levick Magnets Ltd. Ugimag Recoma AG Vacuumschmelze Hanau	HIREM  SAM, SAMLET, NEOM, NEOLET
F. Cast Alnico (over 10 MGOe energy)	The Arnold Engineering Company Crucible Magnetics Co. Thomas & Skinner, Inc.	ALNICO 9 ALNICO 9 AL9, 9Nb
G. Platinum-Cobalt (approx. 10 MGOe)	Vacuumschmelze Hanau	Pt-Co

Table VI lists the specific application areas which were represented by the responses to the survey, and includes a cross-reference to the general PM application areas of Table V.

Table V. A list of general PM application areas which were defined for this program.

A: Electric motors, generators, actuators:

A-1: Medium to large motors, generators, electrical machinery; mostly military applications.

A-2: Medium size specialty motors, generators; mostly industrial applications.

A-3: Small motors for computer accessories, office machines, consumer products, electronic motion control.

B : Microwave/millimeter tubes and devices.

C : Accelerator technology, beam weapons, magnetic resonance imaging (MRI/NMR).

D : Measuring and weighing instruments, inertial guidance devices, etc.

Table VI. Applications represented by survey responses. The terminology is that of the respondents.

Code for General Application	Application Area (Specific Devices)
A-1	Rotating machines. (Permanent magnet alternators and variable reluctance speed sensors).
A-3	Electronic motion control. (PM stepper motors).
A-3	Spindle drives. (Electronically commutated PM motors).
B	Microwave tubes. (Travelling wave tubes).
A-1	Electric motors. (DC torque motor, brushless motor, linear motor).
D	Electronic balances.
C	Accelerator technology. (Dipoles, quadrupoles, sextupoles, wigglers, undulators, MRI magnets).

- A-1 Permanent magnet servo motors. (Brushless and brush types).
- B Magnet focussing of electron beams using periodic permanent magnet (PPM) magnetic circuits. (High-power, high-frequency, coupled cavity TWT's and Klystrons).
- A-2 Electric machines. (Linear electric motors/generators).
- A-1 PM machinery for military applications. (Pump motors, generators, turret drives, actuator motors, etc.)
- A-2 PM machinery for industrial applications. (Electric motors and some generators).
- A-1 Aerospace electric motors, generators. (Rotating field motors, generators to 150kVA).
- B Electron (microwave) tubes, MRI's and biasing PM's for electronic and optical devices. (TWT's, body imagers, filters, circulators and Faraday rotators).
- D Measuring instruments. (Watt-Hr meters, magnetic bearings, eddy-current brakes).
- B Electron beam focusing. (TWT's).

The following is a set of summaries of the responses received. Each of the six areas above is considered individually. Special requirements on magnetic and/or physical properties are identified using the appropriate survey responses to supply much of the detail. The resulting "specifications" represent ranges of required properties and characteristics that HEPM's should have for optimal use in each application area.

The survey encouraged respondents to add comments which they might wish to make about conditions or requirements that were not directly addressed by the questionnaire. At the end of each of the "specifications" is a section called "SURVEY COMMENTS", where these comments are presented in the author's own words. (There was one exception, which was submitted in german and has been translated into english by the report authors. The translation is identified.)

At the end of the six application areas, in Section 5.0, are KJSA comments about trends and specific points in the composite responses that warrent further discussion or analysis.

4.1. APPLICATION AREA A-1: Medium to large motors, generators; mostly military applications.

APPLICATION:

This category includes such devices as brushless and brush-type DC servo and torque motors, linear motors, pump motors, generators to 150 kVA, turret drives, actuator motors and rotating field motors. These may be used in aerospace, ocean or land-based applications.

USE OF PM IN APPLICATION:

In motors and actuators, the permanent magnet is typically located on the rotor or moving core of the machine, at or near the airgap, to produce a flux in the gap. In higher-speed rotating machines the magnet is beneath a retaining structure, which can be magnetic or non-magnetic. The PM may work through a polepiece which focuses the flux to where it is needed. In permanent magnet alternators (PMA), a rotating PM rotor assembly creates a time-varying field to induce a voltage/current in a winding. The PM can be radial or transverse with polepieces. In variable reluctance speed sensors the PM sets up a bias flux which changes as the closure path of the magnetic circuit changes (as by a gear tooth coming near and moving away from the sensor).

SUITABLE MAGNET MATERIALS:

$\text{Sm}_2\text{TM}_{17}$  is the preferred PM material for motors in this category, although AlNiCo, ceramic ferrite,  $\text{SmCo}_5$ ,  $\text{Sm}_2\text{TM}_{17}$  and Nd-Fe-B are also used. If cost and availability were not limitations, the material of choice would generally have 35 to 40 MGOe energy product, good coercive force, good thermal characteristics and should be easy to magnetize. Nd-Fe-B would probably be chosen in many cases if it had a much higher energy product at +200°C and its properties were significantly less dependent on temperature. Neo also exhibits too much corrosion, resulting in poor surface condition and physical deterioration. PMAs and speed sensors are presently being made with  $\text{SmCo}_5$  and Ceramic 5 magnet materials. Planned applications would incorporate  $\text{SmCo}_5$ ,  $\text{Sm}_2\text{TM}_{17}$  and/or other high energy product, high operating temperature materials.

MAGNET ENVIRONMENT:

Severest operating temperature range is -65°C to +290°C; the magnet might see +150°C to +290°C for a time during assembly or bakeout. Temperature cycling would be frequent, typically between extremes of 0°C and +230°C over a period of a few minutes. The magnet may see exposure to water-based cutting and cooling fluids during machining, cleaning fluids like methyl-ethyl ketone (MEK), epoxy coatings, plating baths for Cd or Ni (electro- and electro-less), hydraulic fluids, military/aircraft lubrication oils and fuel fumes. Radiation exposure is possible in isolated instances, possibly in the active zone of a reactor, but without a specific application it is hard to predict the level or type of exposure.

Specific exposure in military applications might include:

TT-S-735	Type I and III (Test Fluid)
VV-F-800	Diesel Fuel Oil
MIL-T-5161	Grade I (Test Fluid)
MIL-T-5161	Grade II (Test Fluid)
MIL-G-5572	Grade 115/145 (Emergency Fuel)
MIL-T-5624	Grade JP4 and JP5
MIL-L-6081	Grade 1010 (Preservative Oil)
MIL-C-7024	Type II (Calibrating Fluid)
MIL-L-7808	Lubricating Oil, Aircraft Turbine Engine, Synthetic Base
MIL-L-23699	Lubricating Oil, Aircraft Turbine Engine, Synthetic Base
MIL-L-83133	Grade JP-8 Fuel
	Epoxy Resins of various types

The magnet typically experiences mechanical loads in operation that are both steady state and vibratory. Magnets may be subjected to 50 KPSI of compression, but with full mechanical support; short-term resistance to cracking is required to facilitate assembly. Tensile strength >40 KPSI is required for multipolar magnets. Prestress of 10 KPSI radial may be applied. Cracking of the magnet can be tolerated in some instances if it can be contained, but not when the magnet is part of a rotating assembly. In many cases, cracking is considered intolerable. Centrifugal force and differential thermal expansion would tend to destroy it. Typical shock loads are up to about 10 G, but can be at the level of about 70 G for 11 microseconds (MIL-STD-810, Method 516.3, Procedure VI), with up to 10,000 G possible. Vibration of 1.5 G peak is possible from 6 Hz to 3000 Hz.

#### REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....	10 kGauss minimum. Should be higher than presently available. 12 kGauss up to ideally >15 kGauss at highest use temperature desired, for improved energy density.
$M H_c$ .....	around 20 kOersted, not critical.
$B H_c$ .....	9 kOe minimum, >11-12 kOersted desired.
$H_k$ .....	Important, should fall at values of $H > 0.5 B_r$ (cgs units). Indicates good loop squareness.
$(BH)_{max}$ .....	25 MGOe minimum, >36 MGOe desired.
$(B_i H)_{max}$ .....	Somewhat important, should be high.
Recoil permeability.....	Close to 1.0, 1.05.
Dynamic recoil energy $(BH)_{rec}$ .....	Listed as not important or not applicable.

The temperature coefficients of coercivity and, especially, of flux are very important in these applications and should be minimized. For example, a zero temperature coefficient of flux density allows relatively constant alternator output across the full operation temperature range.

Highest acceptable magnetizing field to saturate: 25 kG, with 5-10 kG desired.

For applications that must be assembled in the magnetized state it is important that the thermal performance be relatively insensitive to slight under-magnetization. For applications where the magnet is magnetized in the assembly, rapidly rising initial magnetization curves (such as for  $\text{SmCo}_5$ ) are very desirable as they allow optimum magnetization of the assembled magnets with relatively low magnetizing fields.

#### OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

High electrical resistivity is desirable to reduce eddy current losses and the associated heating that result from exposure to alternating magnetic fields. The highest resistivity should be in the plane perpendicular to the direction of magnetization.

Thermal conductivity should be as high as possible, and ideally isotropic, to facilitate removal of the heat that does develop within the device due to friction, windage, eddy current losses etc.

The coefficient of thermal expansion must be well known. It should be close to those of non-magnetic high-strength materials (typically stainless steels) and isotropic if possible. If it differs too greatly from that of surrounding materials it may result in shearing and failure of holding cements/epoxies.

Ideally the material should be machinable with standard machine tools, and not be overly brittle. Brittleness leads to assembly problems. Magnets should be readily grindable in the magnetized state and of sufficient strength as not to crack during normal grinding feeds. The need for grinding is not perceived as a severe problem, but if grinding could be avoided it would be desirable.

#### OTHER PROPERTIES AND FEATURES:

In most applications the magnets will have a thickness in the direction of magnetization of 0.25 inch and more, although REPMS can be used effectively in thinner lengths. Magnets up to 2 inch x 2 inch x 0.5 inch, usually in the form of flat plates, are not uncommon, and larger cross-sections may be required if they can be made. Alternatively, pieces up to 3 inch diameter x 4.5 inch long may also be required.

Magnetization may be simple dipolar or, increasingly, multipolar. (Multipolar patterns are only useful if the magnet material has sufficient tensile strength, >40 KPSI, and lower cost than any presently available rare earth type magnets. Also a high energy product per material cost is required to make multipolar arrangements attractive for larger motor applications.) Both anisotropic and, to a lesser extent isotropic, materials are used. For some applications arc magnets magnetized radially or parallel to the radius are required, mostly of thin radial dimension (0.15 to 0.25 inch) and large cross-sections (1 inch x 1 inch and larger), in arcs of up to  $60^\circ$ . Complete rings with



radial magnetization are desired. The pieces must be physically and magnetically homogeneous (very important). Magnetically they must be uniform within 5-10%.

Magnets are sometimes pre-assembled into composite parts before final assembly, using epoxy resins or heat shrink. Often the PM is bonded to structural, flux-carrying soft iron parts. Some applications could benefit from a "magnetic integrated circuit", for instance where PM's are separated by flux focusing pole pieces as an integral assembly. A composite ring with alternating hard magnetic and softmagnetic sections, and of sufficient strength as to not fall apart when fully magnetized in the circumferential direction with alternating opposing magnetizations could be a useful subassembly for multipole generators.

#### LONG-TERM STABILITY REQUIREMENTS:

10,000 to 50,000 hours of operational life is expected in many applications, within which no magnetic property should change by more than about 5%. Total life (including storage) may be up to 15-20 years. For this reason chemical, shape and magnetic stability must be excellent. B-flux loss especially should not exceed 2-5% over the life of the device; M loss at a specified highest demagnetizing field no more than 5%.  $B_H$  loss cannot exceed 10%. Since many assemblies involve tight mechanical tolerances for interference fits, the outer magnet dimensions must not change over time.

Corrosion is a problem if it degrades the mechanical integrity of the assembly or the overall magnet performance.

4.2. APPLICATION AREA A-2: Medium size specialty motors, generators;  
mostly industrial applications.

APPLICATION:

This category includes such devices as rotating machines of all kinds, linear motors and generators. These may be used in aerospace, ocean or land-based applications.

USE OF PM IN APPLICATION:

Electrical motor rotors and stators (PM field), and some generators. Generally the PM is used to produce fields in airgaps.

SUITABLE MAGNET MATERIALS:

Ferrite magnets are still the primary magnet type for many of these applications. Nd-Fe-B, SmCo<sub>5</sub> and Sm<sub>2</sub>Tm<sub>17</sub> magnets are also being used, and their magnetic properties are adequate for most present applications. Overall cost is the principal driving force, followed by cost of the torque developed and cost of magnetic energy (\$/MGOe). Nd-Fe-B or other higher-energy machineable PM materials would be used if they can meet the requirements.

MAGNET ENVIRONMENT:

Severest operating temperature range is -65 to +150°C. Typical storage is +20 to +50°C, with bakeout temperatures to +150°C. Temperature cycling in operation may be between from +24 to +150°C and back, with 2 cycles/hour. The magnet may see exposure to commercial lubrication oils like silicone oil, and atmospheric contaminants. Radiation exposure is possible in space applications, like power alternators.

The magnet typically experiences mechanical loads in operation that are both steady state and vibratory. Magnets may be subjected to 20 KPSI of compression, but with full mechanical support; tensile stress is also possible. Short-term resistance to cracking is required to facilitate assembly. Cracking of the magnet can be tolerated in some instances, if it can be contained, but not when the magnet is part of a rotating assembly. In some applications cracking is intolerable. Centrifugal force and differential thermal expansion would tend to destroy it. Chipping and surface spalling cannot be tolerated.

## REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....10 kGauss minimum, should be higher than presently available. 12 kGauss up to ideally >15 kGauss at highest use temperature desired, for improved energy density.

$M_H$ .....around 20 kOersted, not critical.

$B_H$ .....9 kOe minimum, >11-12 kOersted desired.

$H_k$ .....Important, should fall at values of  $H > 0.5B_r$ . Indicates good loop squareness.

$(BH)_{max}$ .....25 MGOe minimum, >36 MGOe desired.

$(B_i H)_{max}$ .....Somewhat important, should be high.

Recoil permeability.....Close to 1.0, 1.05.

Dynamic recoil energy  $(BH)_{rec}$ .....Listed as not important or not applicable.

The temperature coefficients of coercivity and, especially, of flux are important in these applications and should be minimized. Tempco of remanence in the range 0.2%/°C over the range 0 to +150°C

Highest acceptable magnetizing field to saturate: 22-25 kG.

Since rotors must often be assembled in the magnetized state it is important that the thermal performance be relatively insensitive to slight under-magnetization. Ultimately, in most industrial applications, cost overrides all other factors.

## OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

High electrical resistivity is desirable to reduce eddy currents and the associated heating that results from exposure to alternating magnetic fields. Highest resistivity should be in the plane perpendicular to the direction of magnetization.

Thermal conductivity should be as high as possible, and ideally isotropic, to facilitate removal of the heat that develops within the device.

The coefficient of thermal expansion must be well known. It should be close to those of non-magnetic high-strength materials and isotropic if possible. If it differs too greatly from that of surrounding materials it may result in shearing and failure of holding cements/epoxies.

Ideally the material should be machinable with standard machine tools, and not be overly brittle. Brittleness leads to assembly problems. Magnets should be readily grindable in the magnetized state and of sufficient strength as not to crack during normal grinding feeds. Nd-Fe-B appears to be more machinable than previous high-energy magnets.

#### OTHER PROPERTIES AND FEATURES:

In most applications the magnets will have a thickness in the direction of magnetization of 0.25 inch and more. Magnets up to 2 inch x 2 inch x 0.5 inch, usually in the form of arcs or rings, are not uncommon. Larger cross-sections may be required if they can be made. Rectangular magnets, as for military applications, are less common. Most applications require arc magnets magnetized in the radial direction or parallel to the radius, mostly of thin radial dimension (0.15 to 0.25 inch) and large cross sections (1" x 1"+). Dipolar magnetization is most common. Multipolar patterns are only useful if the cost is low enough.

Magnet pieces should be physically and magnetically homogeneous. Magnetically they must be uniform within about 10%. Bonding of magnets, especially to a soft iron core, is common in industrial and commercial applications. Composite parts which make a low cost contribution to the total motor cost are desirable, but they also must allow for easy magnetization.

#### LONG-TERM STABILITY REQUIREMENTS:

The long term stability for industrial applications should be in the order of 10 to 30 years with less than 5% overall performance decrease over a 20 year period. This is however helped in general by lower operating temperatures. Chemical stability and shape stability have to be in line with the expected life of the device. Corrosion is tolerable as long as the overall allowable magnetic performance reduction is not exceeded and does not have an adverse affect on size/shape of the magnet. For many industrial applications it would be desirable if the magnets could withstand, in the magnetized state, encapsulation in aluminum by means of aluminum casting.

4.3. APPLICATION AREA A-3: Small motors for computer accessories, office machines, consumer products, electronic motion control, spindle drives.

APPLICATION:

This category includes such devices as PM stepper motors and disk magnet rotors. These are generally for use in land-based applications.

USE OF PM IN APPLICATION:

As disc rotor assemblies. In electronically commutated PM motors, for the main field magnet inside steel rotor rings.

SUITABLE MAGNET MATERIALS:

SmCo<sub>5</sub> and Nd-Fe-B are the primary magnet types being used for disc motor applications; would change over completely to Nd-Fe-B if it were available or lower priced. In small PM motors, ferrites and injection molded Sm-Co magnets are used. Desired is a material with  $B_r$  about 1.3 times that of a Ceramic 8 magnet at about 130% of the cost of Ceramic 8.

MAGNET ENVIRONMENT:

Typical operating temperature range is up to +125°C. Typical storage is 0 to +95°C, with adhesive cure temperatures to +130°C. Temperature cycling in operation may be from +20 to +125°C and back, with 2 cycles/hour. The magnet may see exposure to anaerobic adhesive holding magnet either to aluminum or steel, epoxy resins, acrylic esters and freon. Radiation exposure is a factor in space applications, but types of rays and dosage are not specified.

The magnet typically experiences mechanical loads in operation that are both steady state and vibratory. Vibration can arise from self-induced misalignment vibrations from mechanical imbalances and magnetic force imbalances. For electronically commutated PM motors most of the loading is steady state and arises from centrifugal force. Tensile stress can be above the limits for SmCo<sub>5</sub>. Switching to Nd-Fe-B overcomes this limit, but the tradeoff is more severe temperature limits and rusting of the material. Differential thermal expansion at the bond line also induces stresses; this is particularly bad when Nd-Fe-B is bonded to aluminum.

Cracking is a problem if the magnet comes apart or releases bits into the device. In one particular, larger size disc-type motor application the manufacturer has resorted to "encapsulation", using a very thin, non-magnetic spring steel (as used in watches) bonded to the magnet. This adds cost, but more importantly, strength. With this encapsulation technique the magnet can crack and still operate. In smaller, unencapsulated discs, cracks are unacceptable.

#### REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....12 kGauss minimum.  
 $MH_c$ .....not critical, but must be reasonably high  
without requiring too much  
magnetizing field to develop.  
 $B_H$ .....12 kOe minimum, >12 kOersted desired.  
 $H_k$ .....Listed as not important or not  
applicable.  
 $(BH)_{max}$ .....22 MGOe minimum, as high as possible is  
desired.  
 $(B_iH)_{max}$ .....Listed as not important or not  
applicable.  
Recoil permeability.....Close to 1.0, 1.1.  
Dynamic recoil energy  $(BH)_{rec}$ .....Listed as not important or not  
applicable.

It is essential for a disc motor (and most other PM motors) to have a straight line second quadrant demagnetization curve. The operating point continuously moves over a wide range. Any knee causes demagnetization to occur.

The temperature coefficients of coercivity and, especially, of flux are important in these applications and should be as low as possible.

Highest acceptable magnetizing field to saturate: 20 kG.

#### OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

High electrical conductivity could be a problem if enough eddy currents could be induced in the material from rapid pulsations in reluctance due to slot openings moving by the magnet face, causing extra losses.

Thermal conductivity should be high; a small degree of anisotropy of thermal conductivity should not present any problems.

The coefficient of thermal expansion must be well known. Having anisotropic thermal expansion is a bother to the design, but having tested and sure published specifications which can be used in design considerations is most important. "We don't like surprises."

Good machinability is very important.  $SmCo_5$  can be used for making thin discs, but is difficult. Nd-Fe-B is much better. Mechanical hardness is not required. Brittleness is undesirable because it results in chips and dust that are a problem in small working air gaps. A very thin, low cost coating for Nd-Fe-B is required to assure against oxidation.

#### OTHER PROPERTIES AND FEATURES:

Discs with outside diameter from 25 mm to 100 mm are being made. Thickness ranges from 0.5 mm to 1.1 mm. Inside diameter is a function of the outside, roughly, producing a 15% wide annulus. Discs are magnetized in multipole configurations with the magnetization axial in the disc. A high level of uniformity is required. The design does accomplish some averaging of poles, but material should be of good uniformity. A composite subassembly is now used for disc motors, must be made in-house. A "magnetic integrated circuit" would be desirable, possibly for magnetic encoder applications to achieve absolute position data, not just incremental.

Rings about 3" OD x 2.625" ID x 1" wide with magnetic characteristics and cost equivalent to Ceramic 8 are also being made. These are multipolar with 4 or 8 poles. Material can be isotropic or anisotropic if it gives the required magnetic properties - most being used are anisotropic. For anisotropic arc segments, the magnetization is usually radial. Magnet is bonded to other parts of the device. Uniformity of magnetic properties throughout the magnet volume and throughout all subsequent production is most important. Composite parts or subassemblies, and "magnetic integrated circuits", would be useful if they provide some advantage in cost or performance.

#### LONG-TERM STABILITY REQUIREMENTS:

The disc motor is rated a one year operating life, with overall life including storage and dormancy of 3-10 years. No changes which physically increase the size of the magnet or degrade the energy can be tolerated. Other applications are in the range of 40,000 operating hours over a total life of 100,000 hours. Chemical changes are generally intolerable. The magnet shape and dimensions must be stable, as must the magnetic properties.

#### SURVEY RESPONDENT COMMENTS:

"For a motor manufacturer, the tolerable loss of the B-flux at a defined operating permeance or  $B_d$  level is easiest to monitor. Most cannot measure loss of magnetic moment as seen in operation or loss of normal coercive force  $B_H C$ . For most industrial and commercial motor producers stability or long term aging is a three monkey subject. We can't see it today, we can't control it in time to use it, we may not be here when it breaks."

"Closer control of the magnetic properties on available grades [of magnets] is needed. [Our] producer advises that a  $\pm 5\%$  in the value of  $B_r$  can be expected. This, for example, means it is possible to have a Ceramic 7 part that is on the high side with a  $B_r$  value slightly higher than a Ceramic 8 part with material 5% on the low side.

Closer tolerances on mechanical dimensions should be obtainable without significant cost penalty. A domestic producer insisted that it was

necessary to have a  $\pm 0.007$ " tolerance on the thickness dimension of 0.185" for an arc segment. MMPA Standard Specification for PM Materials was used to justify this broad tolerance on a dimension between two ground surfaces.

Producers also need to improve their ability to provide prototype parts that will closely approximate production parts for PM parts for motors and generators. It is necessary to understand that it is not only necessary to furnish parts with magnetic characteristics that exceed the agreed upon minimums but also necessary that the maximum values are not exceeded. It is very undesirable to "knock down" the magnets when they exceed the maximums."



#### 4.4. APPLICATION AREA B: Microwave/millimeter tubes and devices.

##### APPLICATION:

This category includes such devices as travelling wave tubes, MRI equipment and communications devices. These may be used in aerospace, ocean or land-based applications.

##### USE OF PM IN APPLICATION:

Periodic permanent magnet (PPM) stack in coupled cavity traveling wave tubes over power ranges from 10 to 1000 Watts at frequencies of 10 to 100 GHz; also klystrons and other electron tubes. MRI whole-body imager. Biasing magnets for electronic and optical devices, like filters, circulators and Faraday rotators.

##### SUITABLE MAGNET MATERIALS:

SmCo<sub>5</sub> is presently used for perhaps 60% of TWT's and meets all requirements, 20% is (Sm,Gd)Co<sub>5</sub>, 5% is Sm<sub>2</sub>TM<sub>17</sub>, and 15% is AlNiCo; SmCo<sub>5</sub> is typically temperature stabilized at 250°C. 2-17 types would be desirable for some future tubes. SmCo<sub>5</sub>, Sm<sub>2</sub>TM<sub>17</sub> and Nd-Fe-B are used for other electron tubes and biasing devices. MRI has used mostly high coercivity ferrites, although Nd-Fe-B is being considered.

##### Materials desired if available/affordable:

- Temperature compensated Sm<sub>2</sub>TM<sub>17</sub> (to 800K with 8 kG remanence);
- Temperature compensated Nd-Fe-B (good to at least 250°C);
- Copper-bonded SmCo<sub>5</sub> or Sm<sub>2</sub>TM<sub>17</sub> for improved thermal conductivity;
- Radially oriented or non-oriented SmCo<sub>5</sub> or Sm<sub>2</sub>TM<sub>17</sub> with 16 MGOe or better energy product to allow for radially magnetized magnets for novel focusing applications.

##### MAGNET ENVIRONMENT:

Severest operating temperature range is -100 to +250°C. 400K to 800K for TWT's, 290K for MRI and biasing magnets. Storage is -65 (some say -100) to +150°C, (225K to 350K), with bakeout and qualification test temperatures to +250°C. Temperature cycling is slow but ongoing once the device is in operation, from perhaps -50 to +85°C at a rate of 40°C per hour. Exposure is to air, Salgard potting compounds, salt spray on device, humidity testing 95+% for 10 days..

Magnets may be exposed to silicone-loaded epoxy (Bipax, which is used to cement magnets into place), vacuum (space), and water or oil which are used as cooling fluids.

The magnet typically experiences both steady state and vibratory mechanical loads during operation. Origin of loads is differential thermal expansion, launch conditions for space TWT's, and a vibration table for qualification testing. Sinusoidal vibration to 9-10 G's from

5-20 Hz, random vibration to 26 G's from 20-2000 Hz, acceleration of 45 G's.

Unintentional cracking is undesirable, but does not appear to be a major problem. TWT magnets are cracked in half for installation onto the tube. Further cracking of the magnets during TWT operation or testing could cause magnetic field distortions, thereby degrading performance.

Some TWT's do operate in radiation environments. Type and dosage was not reported. All are exposed to microwave RF during operation.

#### REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....6 kGauss minimum, 8-10 kG typical. no upper limit. Not so important except that it defines the upper limit for  $B_{H_c}$ .

$M_{H_c}$ .....15-30 kOe. Should be safely larger than  $B_{H_c}$  (min.  $M_{H_c} = B_{H_c} + 3000$  Oe).

$B_{H_c}$ .....7.5-10 kOe, desired as high as possible.

$H_k$ .....10 kOe, or as high as possible to assure straight-line B vs. H curve.

$(BH)_{max}$ .....15-25 MGOe.

$(B_i H)_{max}$ .....Listed as not important or not applicable.

Recoil permeability.....As close to 1.0 as possible.

Dynamic recoil energy  $(BH)_{rec}$ .....Listed as not important or not applicable.

The temperature coefficient of  $B_r$  should be  $-0.04$  to  $0.00\%$ /°C. Not nearly as important as the tempco of  $B_{H_c}$ , which is the most important temperature-related property in TWT applications. Desired is  $-0.02\%$ /°C from  $-100$  to  $+250$ °C. This is not yet readily attainable at the required energy products (16 MGOe minimum). Present magnets have about  $-0.06\%$ /°C. Usually  $\alpha(B_r)$  is specified, but  $\alpha'(B_d)$  at an operating point  $-0.5$  to  $-0.7$  would really be more useful.

Highest acceptable magnetizing field to saturate: 40-60 kOe.

TWT magnets operate at very low permeance, 0.25 or less to about 0.8, but rarely see 3rd quadrant operation. It is crucial that the second quadrant demagnetization curve be as linear and as close to  $45^\circ$  as possible. Ideally, recoil permeability should = 1.  $B_{H_c}$  is very critical for TWT applications, and should be as large as possible if high fields are desired. Should be easily varied from magnet to magnet if field shaping is required. Must be as close as possible to  $B_r$  (i.e.  $B_r$  [G] =  $B_{H_c}$  [Oe]), implying a  $45^\circ$  second quadrant B vs. H characteristic.

$H_k$  should be higher than  $B_{H_c}$  to ensure a straight-line B vs. H curve.

Energy product  $(BH)_{max}$  (and intrinsic energy product  $(B_i H)_{max}$ ) should be large for high field applications, although TWT PPM focusing systems are designed to operate near  $B_{H_c}$  and not near the maximum energy product point.

#### OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

Electrical conductivity is not important in TWT magnets, comparable to ferrites is ok.

Heat conduction is of extreme importance, and advancements in the state-of-the-art would certainly be utilized in some high power, high frequency TWT's. Ideally it should be at least as good as that of iron. Current  $\text{SmCo}_5$  is an extremely poor thermal conductor. This can cause thermal gradients within the magnets, leading to undesired magnetic field non-uniformities within the PPM focusing structure. Ideally, if the thermal conductivity of REPM's were improved, it should be anisotropic in the radial direction for washer-shaped magnets, so as to allow for a more efficient transfer of heat away from the beam hole to the package. This is especially true for conduction-cooled space applications, where no external cooling of the magnets (such as water, oil or forced air) is permitted. It is assumed that copper-bonded  $\text{SmCo}_5$  or  $\text{Sm}_2\text{TM}_{17}$  would be the vehicle for improving thermal conductivity. Loop shape should be kept as square as possible and energy product as high as possible, preferably above 12 MGOe. Current packaging is designed around present thermal conductivity values, but new designs could incorporate improvements.

Thermal expansion is taken into account by the TWT designer. Expansion properties should ideally be uniform in all directions to avoid magnet cracking under thermal stresses.

More-machinable materials with less brittleness would reduce costs through simplified fabrication and less breakage during handling and assembly.

#### OTHER PROPERTIES AND FEATURES:

For traditional travelling wave tubes with a PPM structure, the typical magnet geometry is rings, 0.5 to 1.0 inch in diameter by 0.050 to 0.250 inch thick, magnetized axially. Yields on thin rings are low due to fabrication and handling difficulties. The material can be isotropic, but about 90+% of TWT magnets are anisotropic. Other geometries of interest include arc segment with radial magnetization, complete ring with radial magnetization and complete ring or disk with axial magnetization. The magnetic properties should be uniform to within 10% throughout the PM volume. Also uniformity from magnet to magnet is important in PPM stacks, to avoid superimposing unwanted local deviation onto the sinusoidal fundamental; deviation should be <1-2%. Some of the other specialty applications require arcs, rings, trapezoids and cylinders.

#### LONG-TERM STABILITY REQUIREMENTS:

Rated lifetime for a military TWT is up to 200,000 hours of operation; total life including storage time is 10-15 years. Rated lifetime for commercial/industrial TWT's can be as low as 3000-5000 hours; total life including storage time is 2-3 years. Chemical change is of concern only if it changes the magnet's physical dimensions or its magnetic

properties. Tolerances must be held to 0.002-0.003 inch. Generally resistance to air and moisture is required - Salgard provides adequate protection. Long term stability of  $B_r$  and  $B_H$  are of extreme importance. The B-flux at a defined operating permeance, the magnetic moment at a specified highest demagnetizing field and the normal coercive force should not experience any change over the life of the device. The axial field under PPM load should change by 1% or less over 3000 hours. Prestabilization is common, typically 2-4 hours at +250°C and 0.5 permeance.

#### SURVEY RESPONDENT COMMENTS:

"The field required to focus an electron beam in a TWT should not change over the life of the tube more than a maximum of 5%. Otherwise the beam will expand and cause thermal damage to the microwave circuit."

4.5. APPLICATION AREA C: Accelerator technology, beam weapons, magnetic resonance imaging (MRI/NMR).

APPLICATION:

This category includes focussing devices for charged particle beams and radiation sources and magnetic resonance imaging devices. These may be used in aerospace or land-based applications.

USE OF PM IN APPLICATION:

Dipoles, quadrupoles, sextupoles and other multipole magnetic lenses for focusing electron and proton beams, wiggler, undulators, and magnetic resonance imaging (MRI) whole-body imaging equipment for medical and other applications.

SUITABLE MAGNET MATERIALS:

Present designs use Sm-Co, Nd-Fe-B and (infrequently) ferrite magnets. No preference for other materials was expressed.

MAGNET ENVIRONMENT:

Severest +100°C, with some applications down to 20 Kelvin.

In some applications there are large exposures to high frequency electrons (showers), or protons. In some cases doses exceed 1 Gigarad. Radiation damage measurements should be made with the whole magnet block at the same, clearly-defined operating point on the  $B_r(H_k)$  curve.

REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....as high as possible, so long as  $H_k > 1.2B_r$ .  
 $MH_c$ .....no values given.  
 $BH_c$ .....no values given.  
 $H_k$ ..... $> 1.2B_r$ .  
 $(BH)_{max}$ .....no values given.  
 $(B_1H)_{max}$ .....no values given.  
Recoil permeability..... $< 1.1$ , with magnets operating up to  $H_k$ .  
Dynamic recoil energy  $(BH)_{rec}$ .....no values given.

The temperature coefficient of  $B_r$  and  $B_d$  should be as small as possible, ideally zero.

Highest acceptable magnetizing field to saturate:.

OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

Electrical conductivity is usually of no consequence.

Thermal conductivity is unimportant.

Anisotropic thermal expansion is a problem.

Mechanical hardness and brittleness are not big concerns; "usually one can get around these problems".

#### OTHER PROPERTIES AND FEATURES:

As to magnet size, 10-20 cm linear dimensions would be desirable. Non-uniform magnetization would be highly desirable, but only if produced with sufficient accuracy. At present it is necessary to use elaborate, time- and money-consuming methods to correct magnetization errors (both direction errors of  $1^\circ$  and strength errors of 1% cause problems).

Magnets must sometimes be bonded to other parts of the device.

For some applications, different parts of a magnet block may be on very different parts of the magnetization curve, from  $B \text{ approx.} = B_r$  to  $B \text{ approx.} = 0$ , or even  $B < 0$ .

#### LONG-TERM STABILITY REQUIREMENTS:

Rated lifetime for lenses and MRIs is 5-10 years. Chemical changes are important only if they cause a change in the magnetic properties or the dimensions of the magnet. Dimensions stability is important. Magnetic property stability is very important.

#### 4.6. APPLICATION AREA D: Measuring and weighing instruments, inertial guidance devices, etc.

##### APPLICATION:

This category includes measuring instruments like electronic balances and Watt-hour meters. These are used primarily in land-based applications.

##### USE OF PM IN APPLICATION:

Magnets used in devices where the magnetic properties, or a change in the magnetic properties, of an integral magnet effects an indication of a change in the quantity that the instrument or device is intended to measure.

Electronic Balances, an important application where magnets form an integral part of the central force measuring device (electrodynamical converter/compensator).

Watt-hour or Power Meters, where magnetic braking mechanisms and magnetic support bearings are used. The magnetic bearing supports the rotating disk which is used to count the Watt-hours. Magnets are also used as eddycurrent brakes for the aluminum rotor; there are meters with 1,2,3 and 4 braking systems. The same material must be used for both functions in any one meter to assure that the performance variations with temperature are comparable. Electronic power meters are now being developed, using a highly linear and stable Hall element as the sensor. Such systems require accurate and reliable calibrations which will probably involve permanent magnets. A rotating PM is used to produce a 50Hz magnetic field in a 20mm gap of an iron test circuit. The Hall sensor to be tested is placed in this gap and the output is measured. Such a calibration system would require a high energy PM with magnetic properties that are very temperature insensitive.

Electromagnetic Flowmeters: There is a large market which demands very accurate measurements of fluid flow (mostly liquids). The accuracy of the measurement is directly proportional to the stability of the magnetic field in the sensor. This application requires AC fields so as not to introduce electrolysis in the liquid. Temperatures range from very low to very high, and the measurement must generally be made without the sensor contacting the fluid. The use of rare-earth magnets in this application could be of great advantage - PM's are not presently being used at all. Water meters are common and very inexpensive devices whose weak link is the bearing of the turbine or paddlewheel. The bearings, about 5mm diameter, deteriorate rapidly due to contaminants and minerals in the water. A radially oriented magnetic bearing would be a great step forward in increasing the life of this common and important liquid flow metering device.

## SUITABLE MAGNET MATERIALS:

Electronic Balances: Present designs use AlNiCo and  $\text{Sm}_2\text{Co}_{17}$ . Nd-Fe-B would be desired if the temperature dependence of its magnetic properties could be reduced sufficiently.

Power meters: Present designs use AlNiCo, barrium ferrite and Sm-Co magnets. Stronger magnets are desired for some applications to overcome space constraints. Materials with lower temperature coefficients of flux and coercivity are desired.

## MAGNET ENVIRONMENT:

Electronic Balances: Normal operating range is  $0..+40^\circ\text{C}$ , with extended temperature range  $-10..+50^\circ\text{C}$ . Temperatures during shipping may fall to  $-25^\circ\text{C}$  during air freight and  $+70^\circ\text{C}$  during surface shipping. During assembly the magnet may see  $+100^\circ\text{C}$  during bonding of the polepieces. Temperature cycling from  $+50$  to  $+60^\circ\text{C}$  during preaging only.

The magnet may be exposed to normal or slightly corrosive atmosphere (laboratory and industrial environment), and bonding cement during assembly prior to cure.

No radiation exposure except in unusual cases, where a balance is used in a hot cell.

Loading of the PM is steady state for laboratory balances, with vibration up to approximately 100mG in industrial environments. Mechanical stress and loading only to the extent required to keep the magnet mass in place. Cracking of the magnet cannot be tolerated.

Power Meters: Normal operating range is  $-40$  to  $+100^\circ\text{C}$ . Temperature variations are often cyclical, when the meter is mounted outdoors as is often the case in the USA, South America, developing countries, and at construction sites everywhere.

## REQUIRED MAGNETIC MATERIALS PROPERTIES:

$B_r$ .....12-15 kG or more. This is very important.  
 $M_r H_c$ .....high enough so magnet does not lose remanence in open circuit ( $B/H=0.5$ ).  
 $B H_c$ .....high enough so magnet does not lose remanence in open circuit ( $B/H=0.5$ ).  
 $H_k$ .....high enough so magnet does not lose remanence in open circuit ( $B/H=0.5$ ).  
 $(BH)_{\max}$ .....as high as possible, but see comments below.  
 $(B_i H)_{\max}$ .....as high as possible, but see comments below.  
Recoil permeability.....close to 1.0, 1.05  
Dynamic recoil energy  $(BH)_{\text{rec}}$ ..not of great concern.

Electronic Balances: High energy product is important in REPM's, but only if it does not come at the price of remanence at the operating



points  $B/H=1..4$ , ( $B/H=2..3$  typical), and does not increase the temperature dependence of flux. The temperature coefficient of  $B_r$  and  $B_d$  is of ultimate importance to the measuring performance in balance applications; it must be as small as possible (down to  $\pm 10$  ppm/K required, zero would be ideal). Presently, a tradeoff has to be made between a small temperature coefficient and a sufficient remanence.

Temperature coefficient of flux alpha should be defined from:  $-10..+50^\circ\text{C}$  at operating points  $B/H=1..3$  for rare earth PM materials;  $-10..+50^\circ\text{C}$  at operating points  $B/H=15..25$  for AlNiCo PM materials. Tempco of coercivity is of no interest so long as it does not affect tempco of flux and there is no irreversible flux change.

The "knee" of the demagnetization curve must fall below the operating point in open circuit of a permanent magnet having the form of a cylinder with the ratio of diameter to height of approximately 3:1 to 6:1.

Highest acceptable magnetizing field to saturate: For balances, the rare earth PM is presently being magnetized out of the assembly because it is not possible to reach the high fields needed inside the (ferrous) magnet system to saturate the magnet in place. AlNiCo's are still being magnetized inside the magnetic system (which prevents dirt from being attracted into the air gap before final assembly).

Power Meters: Basically the same requirements as for balances. The temperature coefficient of flux and coercivity should be as close to zero as possible.

#### OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE:

Electronic Balances: Electrical conductivity is unimportant so long as some residual electrical conduction is present to prevent buildup of electrostatic charges.

Thermal conduction is of minor relevance. Should be at least about  $10\text{W/mK}$ , higher would not hurt.

Thermal expansion characteristics are not important.

Mechanical hardness is of importance only if it leads to lower production costs, i.e. lower magnet purchase costs.

Brittleness is of prime importance, since loose particles a) change the total flux of the permanent magnet and b) even worse, are kept in the air gap and thus disturb the measuring process.

Power Meters: Basically the same requirements as for balances.

#### OTHER PROPERTIES AND FEATURES:

Electronic Balances: Physical dimensions required are for cylinders, about 30mm diameter x 5mm height up to 40mm dia. x 10mm ht. Flux direction is parallel to the axis of the cylinder, with a single easy

axis for anisotropic magnets. Anisotropic material would be chosen over isotropic if it results in increased flux for a particular application. Uniformity of the magnetic properties is not seen as very important, since the PM is cemented at its two ends to pole pieces of iron; but the temperature dependence of flux should be homogeneous over the whole magnet volume.

#### Power Meters:

#### LONG-TERM STABILITY REQUIREMENTS:

Electronic Balances: Rated operational lifetime is 10..15 years, with a total life including shelf time of 20 years. Chemical changes are not detrimental so long as: a) it does not cause deterioration of flux, b) no particles or dust fall off the surface, and c) bonding strength is not affected. Shape stability is not critical. AS to magnetic property stability, ideally the flux (remanence) at the working point should not change. There are applications where changes of smaller than 0.001% do falsify the measuring results; in other applications a decrease of flux up to 0.5% can be tolerated, if it occurs slowly over the total life. Existing magnet devices are all stabilized by either magnetically or thermally pretreating the magnetic circuit to prevent flux aging.

Power meters: Rated operational lifetime is minimum 30..50 years. The magnetic bearing must have an extremely homogeneous field-distribution all around its circumference so that the rotor does not get pulled to a particular angular position and get stuck there. One speaks of start-up moment (or torque) that is required to overcome all friction and other resistance within the meter. Currents of a few mA are acceptable but the device must also be able to function at 700% of its rated current (i.e. if rated current is 20A, device must function correctly at 140A). Such overload operation may not affect the magnetic properties of the PM's.

#### SURVEY RESPONDENT COMMENTS:

"We assume that the electromechanical meter will not be replaced by electronic power meters. The failure rate of all electromechanical power meters is 0.01..0.03% (vs. 1.0% for military electronic meters), and redundancy would not be cost effective in most cases. The electromechanical meter is also less expensive from a production cost standpoint than electronic meters. This "old-fashioned" electromechanical device receives little notice or attention because of its simplicity, accuracy and reliability, yet it is a technological wonder.

The effect of a magnet in an instrument or measuring system can be positive in nature (a braking magnet should slow something down by interaction between the magnetic properties and the moving part), or it can be negative and result in an error in the measurement (the braking force of the magnet decreases with time, resulting in a change of braking force. If the change is on the order of the magnitude at which the device is calibrated, this can result in an unnoticed change in the instrument's performance and a resulting uncompensated-for error). There now exist measuring instruments which are self-calibrating, but these

are more expensive which means that, in many cases (where cost is important) other methods must be sought. These may include incorporating more stable elements in the instrument, such as the magnet itself."

## 5.0. Observations about Survey Results and Research Efforts to Improve HEPM Materials

### 5.1. Discussion of Survey Results

In simplest terms, everyone wants:

lower magnetic materials cost  
better temperature coefficients of all magnetic properties  
better machinability  
easier magnetizing

The first item on the list could come to pass through Nd-Fe-B. Because of the relatively large raw material supply, production costs for this material could eventually be reduced. There has been little indication of this happening so far, though. Also, the temperature dependence of flux and coercivity of Nd-Fe-B must be substantially improved before it is usable in many applications.

There is much work going on around the world on decreasing the temperature dependence of remanence and coercivity, especially for Nd-Fe-B, but also for  $\text{Sm}_2\text{TM}_{17}$  magnets. This is discussed elsewhere in the report.

Brittleness and poor machinability have long been problems with sintered RE-Co magnets. Sintered  $\text{SmCo}_5$  and  $\text{Sm}_2\text{TM}_{17}$  are both very hard and brittle, and cannot be machined with ordinary machine tools; grinding is necessary. Sintered Nd-Fe-B is similar in behavior but not so brittle. All are difficult to grind in the magnetized state because the removed particles cling to the magnet body, and to all surrounding iron and steel parts. This problem will not likely be overcome except by making the magnetic material so easy to magnetize that it can be ground and assembled in the unmagnetized state and then be magnetized in-situ.

It is difficult to make very thin or very large-volume sintered magnets. In thin pieces, differential thermal expansion and inherent microcracks tend to cause mechanical failure during quench (after sintering). If the thin piece survives the quench, it may break under the forces it experiences during magnetizing. For large volumes, the inside of the piece quenches more slowly than the outside, which generally means it will have different magnetic properties. Differential thermal expansion on cooling also tends to cause failures when quenching very large pieces of sintered magnet. For applications requiring thin or large magnets, the use of bonded magnets instead of sintered magnets may be the best solution.

Low magnetizing field is sought by many engineers. The rare earth-cobalt and rare earth-iron magnets pose new problems with respect to magnetizing field. They need much higher charging fields than lower-energy magnet types (like Alnicos and ferrites) to be fully saturated - 35 to over 50 kOe. If only lower fields are available, the crucial second-quadrant properties depend in a complex manner on the

field strength and the prior magnetic history of the magnet. The high-coercivity magnets exhibit the greatest degree of such behavior.

The older of the precipitation hardened HEPM, including some  $\text{SmCo}_5$ ,  $\text{SmCo}_7$  and the lower- $H_c$  versions of  $\text{Sm}_2\text{Co}_{17}$ , are rather well behaved: 12 to 20 kOe will fully charge them. However, the common  $\text{SmCo}_5$  and similar  $\text{RCO}_5$  magnet types show the magnetization behavior illustrated in Figure 1. The initial magnetization curve of the virgin magnet rises steeply and appears to reach saturation at about 10 kOe. However, the second quadrant demagnetization curve is not fully developed by charging the magnet in such a relatively low field. The remanence and, especially, the intrinsic coercive force and knee field (and therefore also the energy product) have not reached their best possible values. Much higher charging fields are needed to get the performance quoted by the manufacturer.

If a  $\text{SmCo}_5$  magnet was previously magnetized and then field-demagnetized for assembly, it requires an even higher field strength to remagnetize it. The problem is still greater with the newest, high-coercivity 2-17-type magnets, and also with the rapidly quenched Nd-Fe-B materials. The MQ-1 and MQ-2 type materials behave very similarly to  $\text{Sm}_2\text{Co}_{17}$ , MQ-3 somewhat less so. They require fields in excess of 50 kOe to fully magnetize.

Sintered Nd-Fe-B is relatively easy to magnetize, and has an initial magnetization curve very similar to that of  $\text{SmCo}_5$ . The relatively low coercivity of sintered Nd-Fe-B makes it possible to fully magnetize at about 30-35 kOe applied field.

There are efforts under way in Canada and Japan to develop  $\text{Sm}_2\text{TM}_{17}$  magnets that are easy to magnetize in relatively low fields. The desire for magnetizing fields on the order of 5-10 kOe is not presently realizable. Both  $\text{SmCo}_5$  and Nd-Fe-B are very sensitive to undermagnetization - insufficient magnetizing field will fail to develop the second quadrant demagnetization curve to its full potential, and causes more severe temperature dependence of magnetic properties.

## 5.2. Summary: state-of-the-art, trends and possibilities in high energy magnet materials and manufacturing methods for them

Of the older permanent magnet materials predating the rare-earth magnets, the only two that marginally meet our definition of a HEPM are Pt-Co and Alnico 9. Both have been developed close to their limiting properties, their production technologies are long established and mature, and significant future property improvements in these systems are very unlikely. They are also both very expensive, either because of the high-price raw materials (Pt) or the difficult manufacturing process (Alnico 9). - There are hardly any jobs for these magnets that a rare-earth magnet cannot do better and cheaper!

In contrast, the REPM magnet family is still fairly new; and although dramatic progress has been made in recent years expanding and improving this materials family in many different ways, there is still much room

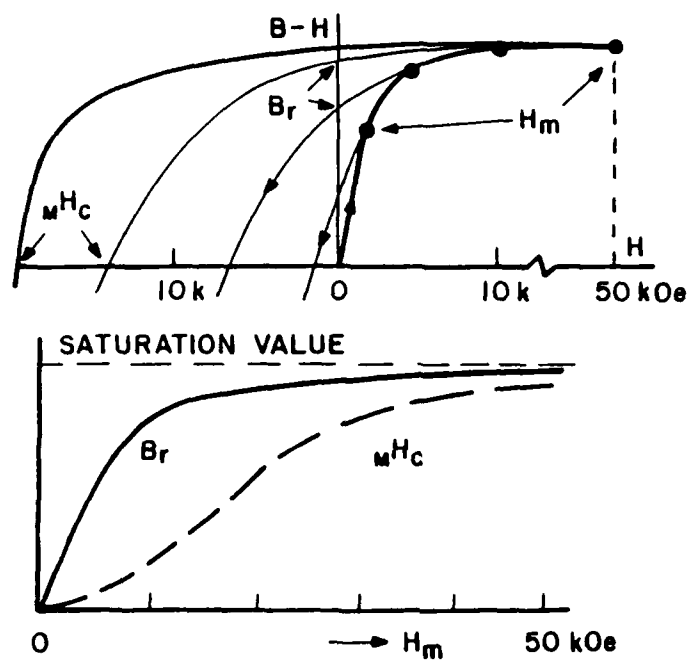


Figure 1. Initial magnetization curves of  $\text{SmCo}_5$ .

for developing alloy modifications and manufacturing processes for improved or specialized magnets. The cost advantages of large-scale production are just beginning to be realized. The necessary industrial plant development has begun at a few companies - mostly in Japan - but it is aimed at producing those magnet types that are used in consumer products such as cameras, audio recorders and VCR's, small motors for automotive and hand-tool applications, computer disc drives, printers, typewriters, etc. Large industrial development efforts now in progress concentrate on Nd-Fe-B magnets, on polymer-bonded REPM because of the ease with which small magnets in the 4 to 10 MGOe range can be made by injection molding and similar plastic-part production methods, and generally on making the magnets cheaper rather than better. These magnets are, of course, not the ones needed for most aeronautical and space applications, or for much of the military hardware.

Particularly, the "fair-haired child" of the current hectic development activity in the PM field, the Nd-Fe-B based materials, have some definite shortcomings when compared to the RE-Co-based magnets that are serious handicaps in many more demanding applications: Their low Curie temperature (about 300 to 350°C versus 700 to 900°C for Sm-Co), high negative temperature coefficients of flux and coercive force, and a much greater propensity for corrosion. Nd-Fe-B magnets also experience some adverse changes in their properties on cooling them into the cryogenic range below 150 K, due to a spin-reorientation in the crystal lattice (which does not occur in Sm-Co). This means that for many applications requiring high operating or temporary exposure temperatures, or very low temperatures, or good thermal and temporal magnetic or chemical stability, cobalt-based REPM will continue to be used. Therefore, more attention should again be given to further developing their full potential.

Let us now consider the techniques by which the different REPM can be produced. Some are basically the same for the Sm-Co and the Nd-Fe-type magnets while others appear to be specific for one material type, at least for now. Until recently, three main manufacturing methods for REPM had been developed:

(1) Most Sm-Co and Nd-Fe is now produced by a powder metallurgical method culminating in a sintering step (performed in vacuum, an inert gas or hydrogen) and generally designed to yield strongly anisotropic magnets of the highest energy density which a given alloy permits. This, then, is the method of choice for making the REPM needed in many military applications. It should be noted, too, that fully anisotropic magnets take the best advantage of the raw materials, which is important when rare samarium and costly cobalt are the primary constituents of the alloy.

(2) Nd-Fe-B (and its derivatives containing small quantities of Dy, other heavy RE, and Co) are also produced by a method in which the molten alloy is rapidly quenched (R/Q) to yield a flaky product that has extremely fine metallurgical grain (such as GMC's Magnequench). In this form the material is chemically more stable and corrosion resistant, which is important for Nd-Fe, and it can be ground to finer particles and further processed into fully dense or into bonded magnets. But this

R/Q material is also essentially isotropic; this limits the attainable remanence and energy product, meaning also that the raw materials are not very efficiently used. Fortunately it has been found that a subsequent hot deformation (near 700°C) can be employed to develop anisotropy in these "R/Q" magnets as well, and current further development of this hot-deformation has already produced laboratory samples with energy densities almost as high as those achieved by sintering.

(3) Cast or presintered Sm-Co, and Nd-Fe-B in the R/Q or hot-deformed state, can be reground into coarse particles and the powder consolidated with a polymeric or soft-metal binder into bonded, or "matrix" magnets. While these have much lower remanence and energy than their fully dense counterparts, and they are less stable at elevated temperatures, they do offer several important advantages - mostly economic: they are not brittle; they can be easily formed into large or very small, even complicated shapes; and inexpensive mass production methods such as injection molding, extrusion or calendaring into sheet can be used. Some plastic bonded Sm-Co magnets have been on the market for over a decade, but only now are they rapidly gaining commercial acceptance. Isotropic bonded Nd-Fe-B (R/Q) is also becoming a fairly common product (but it is not a HEPM!), and it has been demonstrated that anisotropic Nd-Fe powders and matrix magnets can also be produced.

### 5.3. Possibilities for Novel Magnet Processing Methods

The method of making hot-prepressed R/Q Nd-Fe anisotropic by hot plastic deformation was first successfully demonstrated using so-called die-upsetting. However, any of several hot forming methods should yield deformation textures that may be potentially useful in magnetic devices - hot rolling, extrusion (simple and "back extrusion"), swaging, etc. Some such work has been reported in the scientific literature, and promising leads should be developed as possible production methods for Nd-Fe-based magnets. A disadvantage is that the process becomes increasingly complicated, and the magnets so produced may no longer be economically competitive with sintered Nd-Fe.

The Japanese Seiko Epson Comp. has recently announced a new 2-14-1 magnet alloy composition, Pr-Fe-Cu-B, which is a close analog of Nd-Fe-B. Seiko scientists also described a process for making strongly anisotropic magnets from this alloy by a hot-deformation process, particularly the hot rolling of a slab. The process works with a cast ingot and thus circumvents both, the grinding/pressing/sintering as well as the alternative rapid quenching/hotpressing steps. This promises to be a fairly easy and therefore potentially much cheaper mass production method. It might prove adaptable to other alloys (although it was said not to work with Nd-Fe-B) and alternative plastic deformation methods. This should be explored and developed, if promising.

Bonded magnets with better, more temperature-resistant binders are also a very promising avenue along which process development should be pursued. It should be pointed out that the theoretical upper limit of the energy product for bonded magnets - for both, those based on Sm-Co



2-17 and on Nd-Fe alloys - is in the 20 to 25 MGOe range. So, the "best" bonded magnets can indeed be quite respectable HEPM's! If, in addition, they use 2-17 alloy as their magnetic constituent and a metallic rather than a polymeric binder, their upper use temperature can be extended to 150 - 250°C, so that they can qualify for many more applications than plastic matrix magnets. Lab samples with BH-products near 20 MGOe, from both Sm-Co and Nd-Fe-B, have been reported by Japanese industrial laboratories. (Seiko Epson again, and Mitsubishi Steel Mfg. Co.)

At this point it may be useful to summarize the basic processing methods for REPM that are now in commercial use or manufacturing development in the form of a schematic flow-chart diagram. Figure 2 shows schematically the step sequences involved in the four basic production methods discussed above. The salient features of the resulting magnets are indicated in a general way in the last column.

#### 5.4. Possibilities for Useful New and Modified Alloy Compositions

(1) There is much development work in progress at this time aimed at making Nd-Fe-B magnets - the sintered and the R/Q varieties - more serviceable at elevated temperatures by various alloy modifications. The specific objectives are to reduce the temperature dependence of Br and Hc near and above RT, to reduce corrosion, and thus also to increase the flux stability. While this has yielded and will continue to bring some valuable improvements along these lines, no possibility of a dramatic gain in these properties has yet emerged. And there is always a trade-off: the absolute values of remanence, energy product and/or coercivity are reduced. It is also quite apparent by now that only incremental improvements can be achieved by this approach; Nd-Fe-B will remain a high-energy material with a rather low service temperature limit (150 to slightly over 200°C) and high negative temperature coefficients in the useful range.

(2) More promising for the applications demanding higher service temperatures and excellent thermal and temporal stability is work to improve and modify the Sm-Co-based "2-17" magnet alloys. It should still be possible to increase their overall magnetic transition metal content (Co+Fe), to increase the iron content relative to the cobalt, and to minimize the quantities of the essential but nonmagnetic microstructure modifiers, copper and zirconium (or Ti, or Hf). All this would increase the useful flux and energy density, while at the same time reducing the dependence on the strategic main constituent, cobalt metal, and even making the alloy somewhat less expensive at the same time. One unavoidable trade-off is a reduction of the Curie temperature; but that is so high for the presently used Sm-Co magnets (720 to 850°C) that a sacrifice of 50 to 100°C would be acceptable for almost all applications, still leaving the modified 2-17 magnets far superior to any Nd (Pr)-Fe-B magnet types.

(3) Another important aspect for magnets to be used in inertial guidance devices, microwave tubes, measuring instruments, etc. is the possibility of a partial or full internal temperature compensation of the saturation magnetization (and thus of the operating flux density).

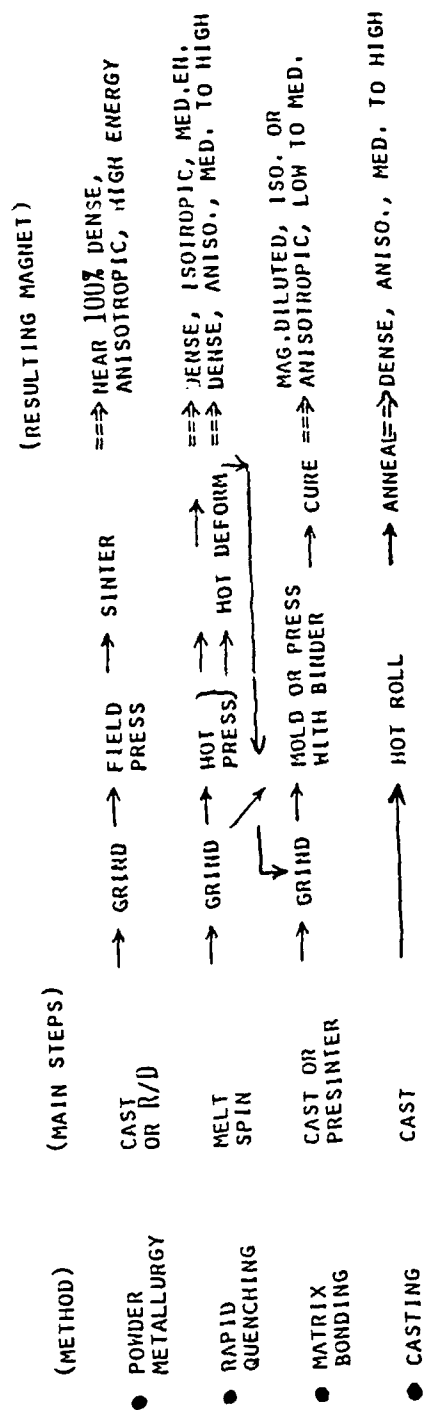


Figure 2. Basic processing methods for rare-earth magnets.

This can be - and has been - done in Sm-Co magnets by alloying-in heavy RE elements such as Gd, Dy, Ho and Er. It works with 1-5 magnets and 2-17. With the latter, magnets having a near-zero temperature coefficient of B in the 50 to 150°C range are theoretically possible, that would still have energy products in excess of 20 MGOe. (This compares with 8-9 for presently produced Sm-Gd-Co 1-5 magnets!) Development work on this prospect could benefit military/space applications in important ways.

(4) Bonded magnets are also possible which are true HEPM,s (10 to over 20 MGOe) while having a much better stability and higher service temperature than present polymer-matrix bonded REPM. The key to this will be the use of a nonmagnetic metal matrix that can be bonded well to the particle surfaces and will protect them from corrosion and loss of coercivity on aging. Temperature compensation in bonded magnets is also possible, using heavy-RE alloys with a positive temperature coefficient to offset the negative temp. coefficient of the principal magnetic component, Sm-Co (or Nd-Fe-B). To achieve such temperature compensation is indeed simpler with bonded than with sintered magnets. The technique, on which KJS Associates has done a lot of work recently, could also be adapted easily to any newly developed, higher remanence 2-17 magnet alloys. (See item 2 above.) It should be noted that the compensation-by-blending approach will also work with Nd-Fe-B, while the possibilities of compensation-by-alloying are very limited for this and other Fe-base REPM.

(5) Finally, the time has probably come to develop 2-17 magnet alloys in which rare-earth elements other than samarium are more extensively used. Sm is increasingly scarce and expensive, as its use by the magnet industry now grows rapidly. The more plentiful and relatively inexpensive RE metals, Ce, Pr, some Nd, and mixtures thereof ("Mischmetal, MM") can replace some of the Sm and still yield very useful magnet properties. Again there are tradeoffs, primarily reduced Curie point and saturation, slightly larger negative temperature coefficients, and reduced stability. But all these properties are so good for Sm-Co 2-17 to begin with that significant reductions can be accepted, and the magnet would still be far superior to Nd-Fe-B and its derivatives for elevated temperature applications. Quite a bit of careful exploratory work along these lines was done in several laboratories around the world in the mid-1970's, but the idea was then laid aside because there seemed enough Sm available and cobalt temporarily became the supply-limited component. No real commercial products resulted, at least not in the USA. But the economic situation regarding use and raw materials supply has changed thoroughly again in recent years, and of course, the appearance of Nd-Fe-B also is having a profound influence.

(6) It should in fact be possible to more or less fill the wide performance gap between presently produced 2-17 Sm-Co and 2-14-1 Nd-Fe magnets by developing alloys and various methods of producing magnets from them as discussed in the preceding paragraphs. Such alloys and the magnet properties could be closely tailor-made to application requirements, representing a close-to-optimum compromise between performance requirements, cost and material availability. The

combination of modified 2-17 compositions and the blending/metal bonding approach is particularly attractive with regard to flexibility in tailoring magnet properties to a particular use without requiring an extensive (and expensive) process development effort for each new magnet type required.

#### 6.0. A Fixture for Testing Demagnetization Curves at Elevated Temperatures.

Previous elevated temperature testing of demagnetization curves in the closed magnetic circuit (with a hysteresigraph) was limited to the temperature range (approx.)  $-150^{\circ}\text{C}$  to  $+200^{\circ}\text{C}$ , using a fixture that was developed at the University of Dayton, Dayton, OH. An improved version of this temperature fixture, the Model "TPF-1", later became a commercial product of KJS Associates. One premise of the proposal for this project, which was borne out by the survey responses, was that modern PM applications frequently require the magnet to operate at temperatures above  $+200^{\circ}\text{C}$ , and often approaching  $+300^{\circ}\text{C}$ . Some engineers predict near-term operational requirements in excess of even that.

To address this need, a fixture was designed and a functional prototype built which, when used with a magnetic hysteresigraph, allows demagnetization curves to be measured on permanent magnets in the closed magnetic circuit over the temperature range  $-197^{\circ}\text{C}$  (liquid nitrogen) to  $+300^{\circ}\text{C}$ . This exceeds the range of temperatures within which most HEPM materials are presently being used.

Although it was designed for use on hard magnetic materials, the fixture can also be used to measure saturation magnetization and (to a certain extent) initial magnetization curves on magnetically soft materials like iron, steel and Fe-Co. The fixture was tested on two magnets that are representative of the types of permanent magnets commonly used in high performance applications - a commercial  $\text{Sm}_2\text{TM}_{17}$  rare earth cobalt magnet and a commercial sintered Nd-Fe-B sample. Details are given below.

#### 6.1. Design Considerations

The TPF-1, on which the new fixture is based, is a temperature-controlled search coil set for use with a dual-integrator magnetic hysteresigraph (Figure 3). The search coil assembly (paddle) has B and H search coils wound of fine polyamid-insulated copper wire on machined ceramic coil forms. An internal thermocouple (TC) measures the sample temperature. The temperature control body ("body") is a two-piece aluminum block with built-in conical poletips, bolted together to form a single, relatively large thermal mass. It has electrical resistance cartridge heaters built in for heating, and internal copper plumbing for the circulation of cooling fluid.

In use, the whole assembly is placed between the pole faces of a laboratory electromagnet (EM) which acts as the magnetic field source. The magnetic flux couples from the EM through its pole faces into the

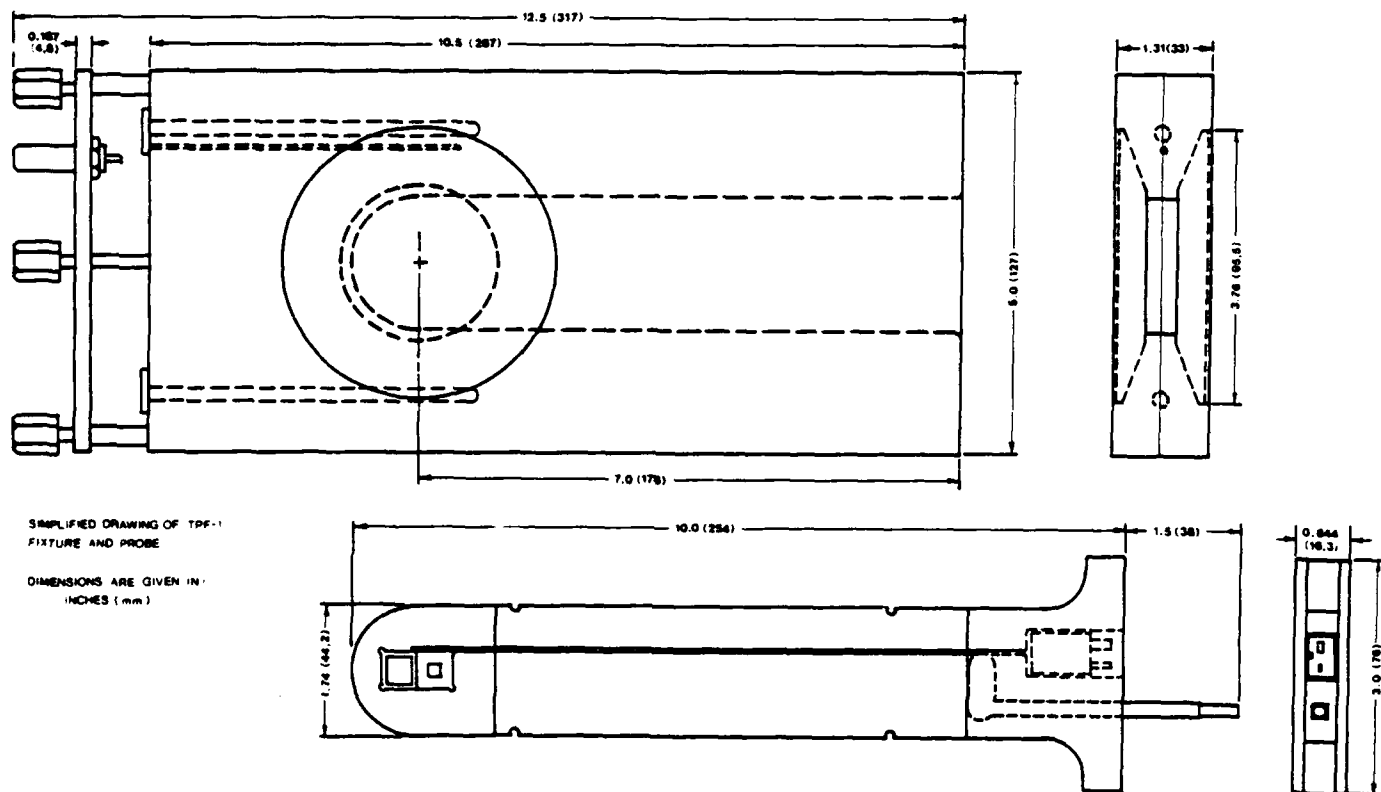


Figure 3. Illustration of TPF-1 temperature fixture, which can be used from  $-150^{\circ}\text{C}$  to  $+200^{\circ}\text{C}$ .

built-in Fe poletips of the body, which focus the magnetizing field on the sample and coil set. The paddle with sample is inserted into a slot in the body. When the paddle is pushed to its stop, the coils and sample are centered on the faces of the built-in poletips. A second TC in the fixture body is used with a temperature controller to regulate the temperature of the fixture.

There are four characteristics that made the TPF-1 fixture unsuitable for the purposes of this project:

- a) It is limited to a maximum use temperature of  $+200^{\circ}\text{C}$  by the insulation on the search coil wire and by the epoxy used to hold the lead-in wires and search coils in place;
- b) even if the wire insulation and epoxy were not limiting factors, the number and placement of electrical heating rods was insufficient for continued operation above  $+200^{\circ}\text{C}$ ;
- c) the distance between the built-in poletips is fixed, so that all samples must be machined to a precise length in the magnetization axis if an accurate measurement is to be made. This is a considerable inconvenience and results in much costly machining of magnet samples;
- d) because the search coils and lead-in wires are epoxied into the paddle, the whole paddle must be rebuilt if a coil is damaged or broken.

The new fixture, designated the TPF-300, was designed to overcome these limitations.

Figure 4 shows an assembly drawing of the TPF-300 fixture body. The search coil assembly is shown in Figure 5. The temperature control body still consists of two bolted-together aluminum body halves, but is more compact than was its predecessor. The internal polepieces are made of iron-cobalt (Fe-Co) to provide the maximum possible magnetizing field. Instead of being conical, these polepieces are stepped (like a wedding cake), which significantly reduces machining and assembly costs without a significant loss of magnetizing field. This change also relates to the method chosen for making the air gap in the fixture adjustable.

One polepiece is bolted in place permanently in the fixture. Its surface is flush with the inside of the fixture body on one side. The other polepiece has an external thread, so it can be screwed into and out of the fixture body. To minimize wear problems, the Fe-Co moves against a threaded bronze insert instead of against the much softer aluminum. The air gap in the fixture can be adjusted from 6 mm up to 15 mm by simply turning the moveable pole until the desired gap is achieved. An adjustable guide keeps the search coil paddle centered in the air gap and around the sample.

The search coil end of the paddle is also made from two parts that are screwed together. Pockets are machined into both sides of the paddle end, which contain the wound coil forms when the paddle is assembled. The coil forms are made of ceramic, and the coils themselves are wound of fine copper wire with a powdered ceramic insulation that can

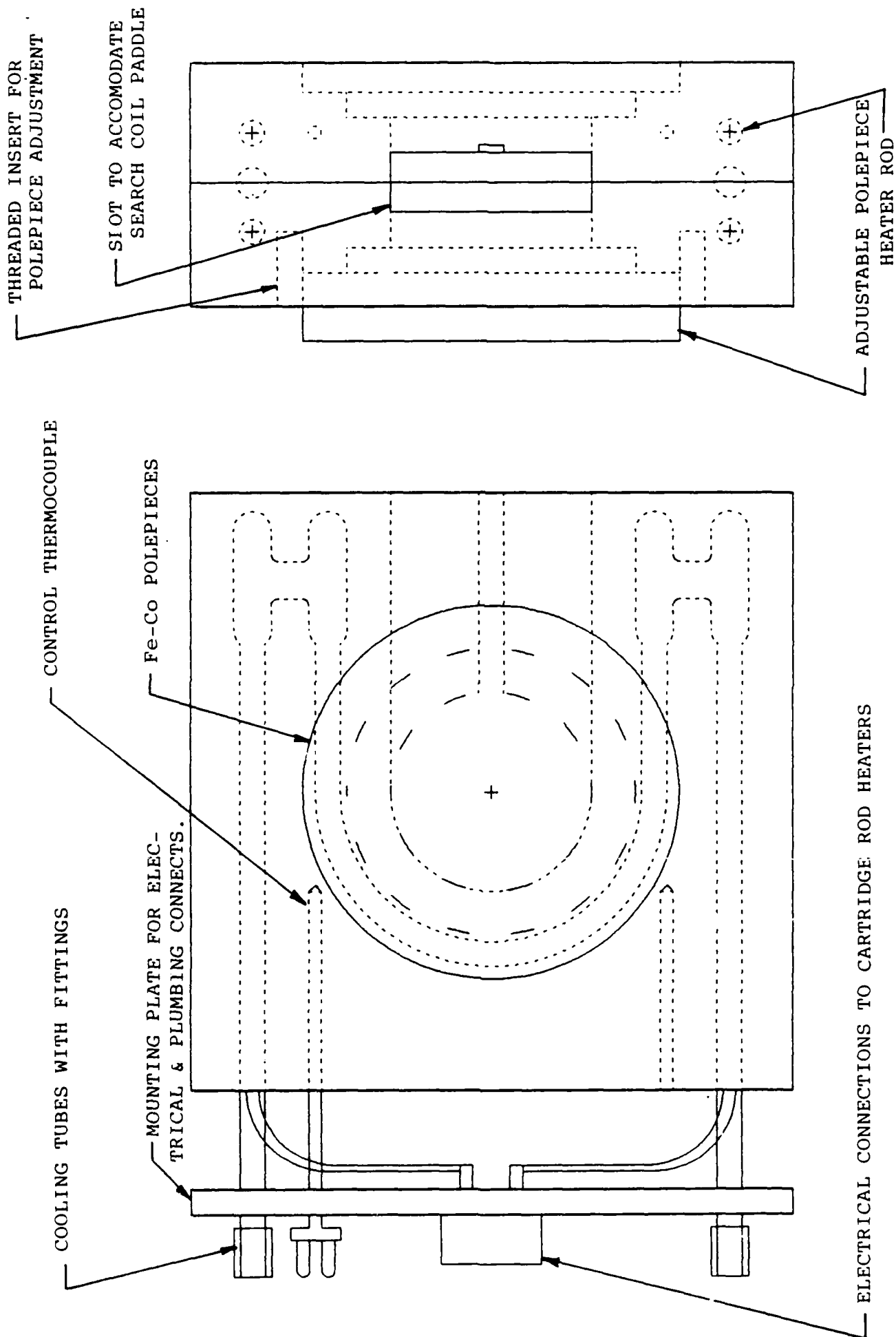


Figure 4. Illustration of temperature control body for TPF-300 fixture, which can be used from  $-197^{\circ}\text{C}$  to  $+300^{\circ}\text{C}$ .

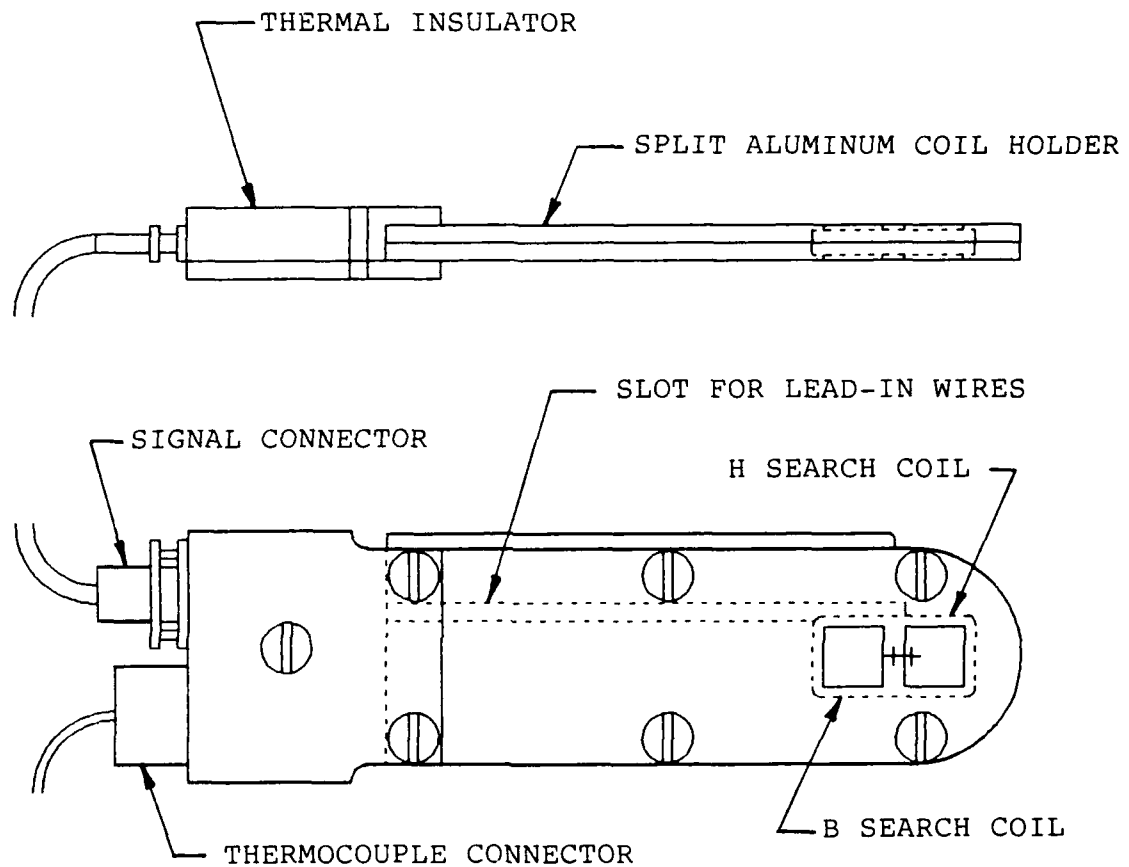


Figure 5. Illustration of search coil paddle for TPF-300 fixture. The coil forms are made of machinable ceramic, and the coils are wound of ceramic-insulated copper wire.



withstand temperatures up to about 500°C. A fine-wire TC bead is placed in contact with the coil form to measure the temperature of the sample. Type T copper-constantan thermocouple wire was chosen because it is non-magnetic and therefore least likely to cause local disturbances in the magnetic field near the sample.

If a wire breaks or a short circuit forms in the search coils the paddle can be disassembled, the damaged coil(s) rewound, and the whole assembly put back together without any machining required. The assembled coil end is attached to one end of an extension made of a good thermal insulator. The other end of the insulating plate contains the search coil wire terminations, connections to the heavier lead-in wire, and the TC connector. By separating the connections from the heated aluminum part where the coils are, the search coil assembly should become more reliable, and less heat is conducted away from the fixture by the paddle.

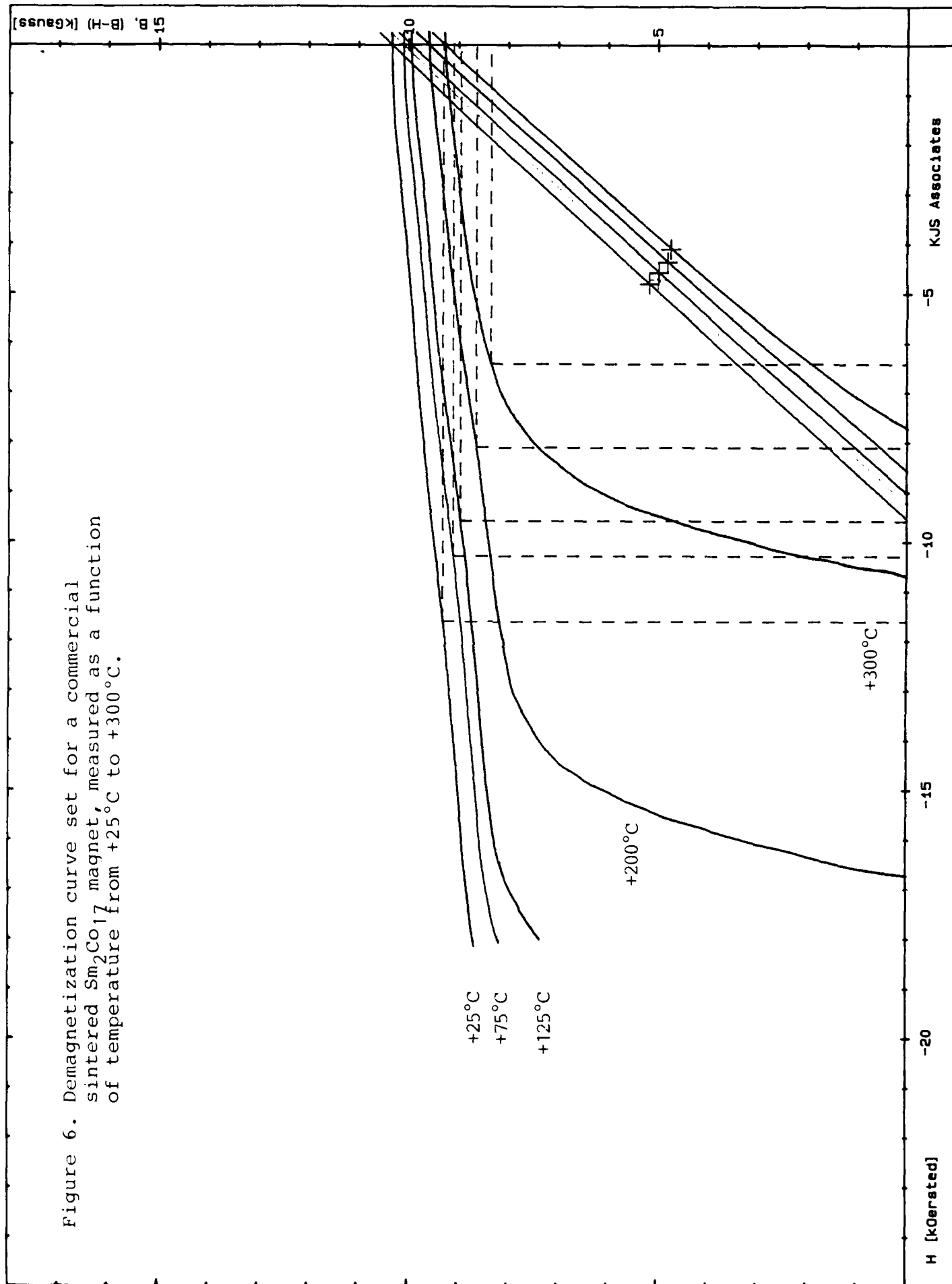
Normal operation requires a temperature controller. A second thermocouple is placed in the thermal body for use as a control TC. (Controlling the fixture temperature using the sample TC results in a loose control loop that hunts and seeks rather than stabilizing at the setpoint temperature.)

## 6.2. Representative Measurements on $\text{Sm}_2\text{Co}_{17}$ and Nd-Fe-B Magnets

The search coil paddle of the high temperature test fixture was used to measure demagnetization curve sets on two types of commercial anisotropic sintered HEPM material, a  $\text{Sm}_2\text{Co}_{17}$  magnet (Figure 6 and Table VII) and a Nd-Fe-B magnet (Figure 7 and Table VIII). Both samples were in the form of 1 cm cubes and were measured along their easy axis of magnetization. The sample under test was magnetized in a 100 kOe pulse field at room temperature prior to each measurement. After the fixture had stabilized at the desired test temperature, the sample was pre-heated for 2 minutes before testing. Then a forward magnetic field of about 18 kOe was applied in the closed magnetic circuit, followed by the measurement of the second quadrant demagnetization curve. After the sample had cooled to room temperature it was again pulse magnetized prior to testing at the next temperature. The signal processing and plotting was done using a KJS Associates Model HG-500 computerized magnetic hysteresigraph.

The two samples for which demagnetization curve sets are depicted here are representative of what is commonly available as commercial sintered magnet material in the categories of precipitation-hardened  $\text{Sm}_2\text{Co}_{17}$  and ternary sintered  $\text{Nd}_2\text{Fe}_{14}\text{B}$ . Obviously there will be wide variation in specific properties among the various grades of material. (For more information on this topic see Section 3.0 above.) Generally, increases in coercivity are accompanied by decreases in remanence. Knee field  $H_k$ , an indicator of loop squareness, is much less temperature sensitive for materials with very high intrinsic coercivities than it is for those with low  $M H_c$  ( $H_{c1}$ ).

Figure 6. Demagnetization curve set for a commercial sintered  $\text{Sm}_2\text{Co}_{17}$  magnet, measured as a function of temperature from  $+25^\circ\text{C}$  to  $+300^\circ\text{C}$ .



These curves are presented here for several reasons. They show that the newly designed test fixture can be used to measure demagnetization curves at temperatures up to +300°C, and that it survived several cycles up to that maximum temperature under test conditions. They give some first-hand indication of the numerical values of salient magnetic properties and their temperature dependence for the two most important types of HEPM materials currently available. And finally, the curve sets illustrate what is probably the most important and most useful type of information about a magnetic material that can be provided to engineers by magnet manufacturers: actual complete demagnetization curves over a range of temperatures that are representative of conditions in which permanent magnets are frequently used.

Because the search coil paddle for the test fixture was completed at the very end of the timeframe for the performance of this contract, the curve sets include only five elevated temperatures including room temperature. A complete data set for a commercial magnet material should include demagnetization curves measured from at least -55°C to +300°C, in steps of 25 or 50 degrees. Clearly the temperature range and increment requirements will vary from application to application, but presenting families of curves with a reasonably small step size makes the process of choosing the correct material for a given device much easier.

Table VII. Salient magnetic properties as a function of temperature for sample number MS-1056, a commercial sintered  $\text{Sm}_2\text{Co}_{17}$ . The associated demagnetization curves are shown in Figure 6.

Temp. [°C]	Br [kG]	MHc [kOe]	BHc [kOe]	Hk [kOe]	BHmax [MG0e]
+25	10.34	>18.17	9.54	11.61	24.9
+75	10.11	>18.09	9.22	10.28	23.6
+125	9.95	>18.08	9.02	9.58	22.8
+200	9.60	16.73	8.57	8.10	21.0
+300	9.27	10.71	7.72	6.42	19.5

Figure 7. Demagnetization curve set for a commercial sintered  $\text{Nd}_2\text{Fe}_{14}\text{B}$  magnet, measured as a function of temperature from  $+25^\circ\text{C}$  to  $+300^\circ\text{C}$ .

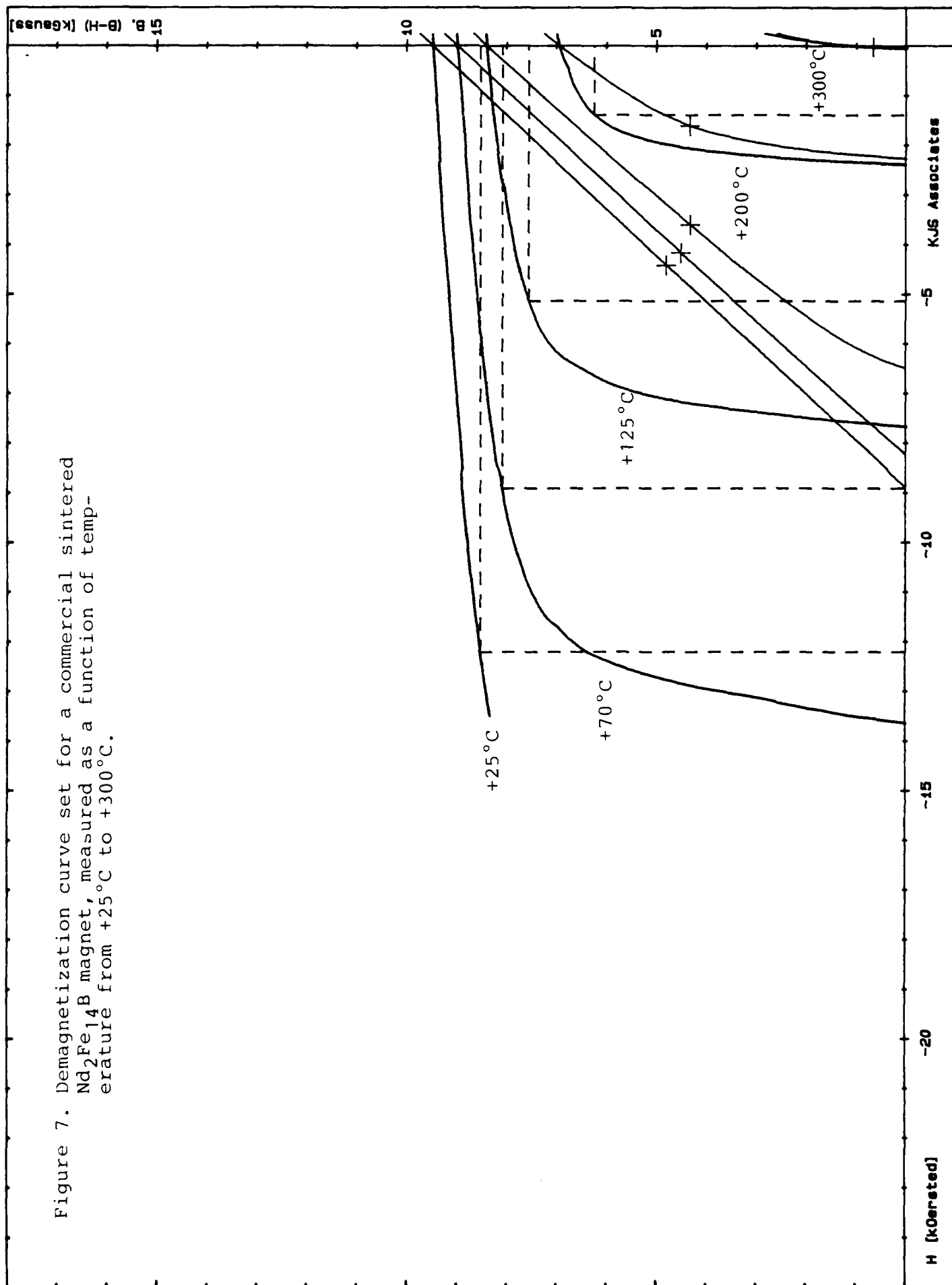


Table VIII. Ssalient magnetic properties as a function of temperature for sample number MS-457B, a commercial sintered  $\text{Nd}_2\text{Fe}_{14}\text{B}$ . The associated demagnetization curves are shown in Figure 7.

Temp. [°C]	Br [kG]	MHc [kOe]	BHc [kOe]	Hk [kOe]	BHmax [MG0e]
+25	9.48	>14.00	8.89	12.21	21.2
+70	8.98	13.64	8.22	8.90	18.8
+125	8.40	7.67	6.49	5.13	15.6
+200	6.94	2.38	2.27	1.39	7.0
+300	0.87	0.04	0.04	0.01	0.0

### 7.0. Conclusions

The information gathered about high-energy permanent magnet materials and applications under this project does not yield any great surprises. It did confirm a number of assumptions that had been made about PM materials requirements. In general terms, devices containing HEPM's are being designed for higher temperature operating environments and/or for applications where the level of flux from the magnet should be independent of temperature variations. From the materials standpoint, these two conditions are somewhat related. To make a PM material operate at a higher temperature it is necessary to improve its behavior at the high end of the use temperature range. This may typically result in higher Curie temperatures and perhaps higher flux levels. Coercivity must also generally be increased in REPM's in order to improve high-temperature performance. An improvement in temperature stability of properties tends to go hand in hand with increased upper use temperature.

In the case of Nd-Fe-B, much of the present materials development work focuses on surface protection and improved chemical stability. There is also work being done on increasing its Curie temperature. Both of these characteristics must be improved before Nd-Fe-B will find a place in the more sensitive and critical applications.

For  $\text{Sm}_2\text{TM}_{17}$  materials, several companies are actively pursuing temperature compensated magnets which have specific temperature coefficients of remanence over temperature ranges of interest to their customers. There are such materials available in the marketplace now, as indicated in Tables III and IV. These efforts must be ongoing and should be strongly supported, since many of the current and planned defense-related applications require better temperature stability of PM properties.

There is little information available about the behavior of high energy permanent magnets above about +200°C. It would be a worthwhile program to obtain samples of all of the HEPM materials identified in this report and thoroughly characterize their magnetic behavior over the full potential use-temperature range. Since KJSA has, under this contract, developed a fixture for measuring demagnetization curves over a wide temperature range, such a project would make a logical SBIR Phase II. KJS Associates plans to submit a Phase II proposal addressing that point.

APPENDIX I. List of manufacturers of high energy permanent magnets.

HOME OFFICE ADDRESS

USA SALES OFFICE  
(for foreign companies)

The Arnold Engineering Company  
300 West Street  
Marengo, IL 60152  
(815)568-2000 Marengo  
(312)263-6300 Chicago

Crucible Magnetics  
A Division of Crucible Materials Corp.  
101 Magnet Drive  
Elizabethtown, KY 42701  
(502)769-1333

Electron Energy Corporation  
329 Main Street  
Landisville, PA 17538  
(717)898-2294

Hitachi Magnetics Corporation  
Edmore, Michigan 48829  
(517)427-5151  
FAX (517)427-5571

Hitachi Metals America  
2400 Westchester Ave.  
Purchase, NY 10577  
(914)694-9200  
FAX (914)694-9279

Hoeganaes Corporation  
Magnetics Division  
River Road & Taylors Lane  
Riverton, N.J. 08077  
(609)829-2220

IG Technologies, Inc.  
405 Elm Street  
Valparaiso, IN 46383  
(219)462-3131

Krupp Widia Magnettechnik  
Postfach 10 21 61  
D-4300 Essen 1  
FRG/West Germany  
(0201)7240-1

International Magnoproducts, Inc.  
8120 Sheridan Blvd.  
Suite C-310  
Westminster, CO 80003  
(303)650-1903  
FAX (303)650-5010

Magnequench  
a Business Unit of Delco Remy,  
Division of General Motors  
6435 S. Scatterfield Rd.  
Anderson, IN 46013  
(317)646-5050  
FAX (317)646-5060

Namiki Precision Jewel Co. Ltd.  
22-8, 3-chome, Shinden  
Adachi-ku, Tokyo, Japan  
919-0101

Namiki USA  
One World Trade Center  
Suite 8905  
New York, NY 10048  
(212)466-0718  
FAX (212)466-0749

Ovonix Synthetic Materials Co.  
1788 Northwood Drive  
Troy, Michigan 48064  
(313)362-1290  
FAX (313)362-4043

Philips ELCOMA  
P.O. Box 218  
5600 MD Eindhoven  
The Netherlands  
31 4072 3304

North American Philips Co.  
Amperex Electronic Co.  
6045 Atlantic Blvd., Suite 123  
Norcross, GA 30071  
(404)496-5648  
FAX (404)446-6116

Seiko Epson Corp.  
Motor and Magnet Sales Group  
3-5, Owa 3-chome, Suna-shi  
Nagano-ken, 392 Japan  
(0266)27-8911  
FAX (0260)28-7498

International Magnetics Inc.  
3103 Cascade Drive  
Valparaiso, IN 46383  
(219)465-1998  
FAX (219)462-5146

Shin-Etsu  
Magnet Dept., Electronic Materials  
6-1, Ohtemachi, 2-chome  
Chiyodoku, Tokyo, Japan  
03-246-5246  
FAX 03-246-1335

Shin-Etsu USA  
Los Angeles Liaison Office  
431 Amapola Ave.  
Torrance, CA 90501  
(213)533-8559  
FAX (213)533-8936

Sumitomo Special Metals Co., Ltd.  
No. 3 Sumitomo Bldg.  
5-22, Kitahama, Higashi-ku  
Osaka 541, Japan  
06-220-8865  
FAX 06-226-0089

SSMC USA  
Los Angeles Office  
23326 Hawthorne Blvd.  
Suite 360, Skypark 10  
Torrance, CA 90505  
(218)378-7886  
FAX (213)378-0108



Swift Levick Magnets, Ltd.  
Foremost Works, Grange Mill Lane  
Wincobank  
Sheffield S91MW, England, UK  
(0709)550099  
FAX (0709)560482

TDK Electronics Co., Ltd.  
13-1, Nihonbashi 1-chome  
Chuo-ku, Tokyo 103, Japan  
(03)278-5111

Thomas & Skinner, Inc.  
1120 East 23rd Street  
P.O. Box 150-B  
Indianapolis, IN 46205  
(317)923-2501

Thyssen Edelstahlwerke AG.  
Magnetfabrik Dortmund  
Ostkirchstrasse 177  
D-4600 DORTMUND 41 (Aplerbeck)  
FRG/West Germany  
(0231)4501-0  
FAX (0231)45012-81

Ugimag Recoma AG.  
Industrie Strasse 297  
CH-5240 Lupfig/AG  
Switzerland  
41(56)94 90 66  
FAX 41 (56) 94 90 81

Vacuumschmelze GMBH  
Hanauworks  
GrunerWeg 37  
P.O. Box 2253  
D-6450 Hanau 1  
(06181)362-1  
FAX (06181)362645

Swift Levick, Inc.  
34 Industrial Way East  
P.O. Box 1204  
Eatontown, N.J. 07724  
(201)389-4411

TDK Corp. of America  
Los Angeles Branch  
2041 Rosecrans Ave., Suite 365  
El Segundo, CA 90245  
(213)644-8625

Recoma, Inc.  
Div. of Aimants Ugimag  
2 Steward Place  
Fairfield, NJ 07006  
(201) 575-6970  
FAX (201)226-3816

US OFFICE  
Vacuumschmelze  
c/o Siemens Components, Inc.  
186 Wood Ave., South  
Iselin, N.J. 08830 USA  
(201) 494-3530

APPENDIX II. List of respondents to user survey/questionnaire  
on HEPM applications.

(In alphabetical order by company name.)

A.O. Smith  
Electrical Products Company  
531 N. Fourth Street  
Tipp City, OH 45371-1899  
Mr. Steven Dellinger

Clifton Precision  
Division of Litton Industries  
Marple at Broadway  
Clifton Heights, PA 19018  
Mr. Thomas Lemley

General Electric - AE  
1 Neumann Way, MS A-320  
P.O. Box 156301  
Cincinnati, OH 45215-6301  
Dr. Eike Richter

Hughes Aircraft - EDD  
Bldg. 230/1165  
3100 W. Lomita Blvd.  
Torrance, CA 90509  
Mr. Anthony C. Morcos

Industrial Drives  
Div. of Kollmorgen Corp.  
201 Rock Road  
P.O. Box 2990  
Radford, VA 24141  
Mr. Burley Semones

Inland Motors  
Division of Kollmorgen Corp.  
501 First Street  
Radford, VA 24141  
Mr. Robert Fisher

Landis & Gyr Zug AG  
CH-6340  
Zug, Switzerland  
Dr. Friedrich E. Wagner

Lawrence Berkeley Laboratory  
Univ. of California at Berkeley  
1 Cyclotron Road  
Berkeley, CA 94720  
Dr. Klaus Halbach

Mettler Instruments A.G.  
CH-8606  
Greifensee, Switzerland  
Dr. Remy Glardon

NASA Lewis Research Center  
21000 Brookpark Road  
Building 28  
Cleveland, OH 44135  
Dr. Jan Niedra

Portescap U.S.  
36 Central Avenue  
Hauppauge, NY 11788  
Mr. Frank Arnold

Semicon Associates  
Division of Ceradyne  
1801 Old Frankfort Pike  
Lexington, KY 40510  
Mr. Louis R. Falce

Sundstrand Advanced Technology Group  
4747 Harrison Avenue  
Rockford, IL 61125-7002  
Dr. Jayant Vaidya

Unison Industries  
P.O. Box 17880  
Jacksonville, FL 32245-7880  
Mr. Zouheir Abdelnour

University of Kentucky  
Electrical Engineering Dept.  
Lexington, KY 40506  
Dr. Syed A. Nasar

U.S. Army  
Electronics Technology and Devices Laboratory  
SLCET-ES  
Fort Monmouth, NJ 07703  
Dr. Herbert Leupold

Varian Microwave Tube Division  
611 Hansen Way  
Palo Alto, CA 94303  
Ms. Marianne McKissock

APPENDIX III. Text of survey/questionnaire for magnet users.

QUESTIONNAIRE FOR MAGNET USERS

TO ASSIST IN DEVELOPING SPECIFICATIONS FOR DIFFERENT  
APPLICATION CATEGORIES OF HIGH-PERFORMANCE MAGNET MATERIALS.

A: SPECIFY APPLICATION

1. General application area
2. Device type
3. Specific magnet use/position of PM in device

(If available, please provide or give reference to a technical description of device or enclose sales literature.)

B: SUITABLE MAGNET MATERIALS

1. FM type now used
2. Material desired if it were available/affordable

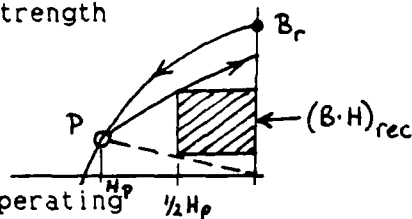
C: WHAT ENVIRONMENT DOES THE MAGNET SEE?

1. Regarding temperature extremes
  - a. During operation of the device or machine
  - b. In the dormant state between uses
  - c. Temporary conditions. (During assembly, bakeout, etc.)
  - d. Frequent temperature cycling? (Range? Cooling/heating rates?)
2. Atmosphere, fluids, cements, coatings in contact?
3. Radiation exposure? (Please specify type, dose, intensity, duration.)
4. Mechanical loads on magnet
  - a. Steady state or vibratory ?
  - b. Type of stress, extreme levels
  - c. Origin of load (centrifugal force, differential thermal expansion, pre-stressing by design, etc.)
5. Can cracking of magnet in use be tolerated?

## D: REQUIRED MAGNETIC MATERIALS PROPERTIES

(Listed are commonly used quantities; not all are pertinent for all uses; please state which are most important. Are numbers given acceptable minima, maxima or most desirable values?)

1. Residual induction,  $B_r$  (at  $H=0$ ) (= zero-field "remanence")
2. Intrinsic coercive force,  $M H_C = H_{Ci}$  (at  $M=0$ )
3. "Normal" coercive force,  $B H_C = H_C$  (at  $B=0$ )
4. "Knee field,"  $H_k$ , where  $B_i = B - H = 0.9 B_r$  on the intrinsic demagnetization curve. If this quantity is inappropriate, please give an alternative property which you prefer for characterizing "loop squareness."
5. Static energy product,  $(B \cdot H)_{\max}$
6. Intrinsic energy product,  $(B_i \cdot H)_{\max}$
7. Recoil permeability,  $\mu_{\text{rec}}$ . (Specify permeance or field-strength range of concern)
8. Dynamic recoil energy product,  $(B \cdot H)_{\text{rec}}$ .  
See sketch for definition.
9. Temperature coefficient,  $\alpha'(B_d)$  of the remanence at an operating point,  $(H_d, B_d)$ , or at a specified permeance; or  $\alpha(B_r)$  if appropriate. Please specify the range or single temperature for which  $\alpha$  is defined.
10. Temperature coefficient,  $\beta(M H_C)$ , of the intrinsic coercive force. Specify range or temperature for which defined.
11. More general alternative to 9 or 10: Is a temperature-independent flux or a controlled temperature function of the operating-point flux needed over a wider temperature range? (Please elaborate!)
12. Magnetizing of magnet or subassembly: Maximum acceptable peak charging field to develop the above properties?
13. Please specify any other properties that are important in your application.



#### E: OTHER PHYSICAL QUALITIES/PROPERTIES OF IMPORTANCE

Please indicate those that matter for this application; where known, give numerical values for desirable or acceptable properties.

1. Electrical conduction. - Is it important that the magnet be a good conductor, or else a good insulator? If so, please state desired conductivity or resistivity values.  
The conductivity may be different for different current directions (anisotropy); is this of any consequence?
2. Heat conduction. - Is it an important property? If yes, state desired thermal conductivity values.  
May also be anisotropic; is this of consequence?
3. Thermal expansion and its anisotropy.
4. Mechanical hardness (relates to machinability)
5. Brittleness (relates to physical integrity and ease of handling)

NOTE: High-coercivity magnet materials are generally very hard and brittle. However, the bonded magnets are usually not, depending on the properties of the binder used.

#### F: OTHER PROPERTIES AND FEATURES

The following features have influence on the most suitable production method and on the cost of the finished magnets.

1. Approximate size of magnet used (or desired single-piece size, if it were producible).
2. Characteristic shape of magnet needed or desired. (Flat plates, arcs, rings, etc. The thinnest dimension is often a limiting factor in production.)
3. Magnetic flux directions in the magnet:
  - a. Simple dipolar vs multipole magnetization pattern?
  - b. Is a magnetically anisotropic or isotropic material desired?
  - c. If anisotropic, which magnetization pattern? - Some possibilities:
    - \* Single easy axis (for straight-through magnetization or a multi-pole pattern of strictly antiparallel domains)
    - \* Multipole magnetization with flux path curving within the magnet.
    - \* Arc segment with radial magnetization (arc angle?)
    - \* Arc with parallel magnetization through thickness.
    - \* Complete ring with radial magnetization
    - \* Complete ring or disc with axial magnetization

4. Uniformity of the magnetic properties throughout the sample volume.
5. Must the magnet be bonded to other parts of the device? (Structural or other magnetic materials.)
6. Is a composite part/subassembly now used, or would it be desirable to use one? (PM + softmagnetic + structural parts fabricated and supplied to you as a unit.)
7. Would a "magnetic integrated circuit" be desirable? (E.g., powders of different materials combined in a single bonded compact.)

#### G. LONG-TERM STABILITY REQUIREMENTS

1. Rated life time of device:
  - a. Under operating conditions
  - b. Total, including dormant and storage times
2. Chemical Stability. - How detrimental are long-term chemical changes on the surface of the magnet material?  
  
(Consider atmospheric corrosion of exposed surfaces or under protective coatings; diffusion reactions with binder materials, cements or coatings; etc.)
3. Shape Stability. - How critical is geometric integrity, retention of precise dimensions and shape?  
  
(Problems can arise from chemical corrosion, surface spalling under internal stresses, slow progression of cracks, swelling of binders due to heat and moisture, flowing of binders under sustained centrifugal or other external stress, radiation effects.)
4. Magnetic Property Stability. - How important is the retention of the initial magnetic properties over long period of time? Which are the critical properties that must be stable?

NOTE: Changes of the hard magnetic properties with time will inevitably occur, for a number of reasons. Their progression depends on the environment of the magnet and is generally hastened by elevated temperature exposure. These "aging effects" vary strongly for different materials; but they also depend equally strongly on the magnetic operating state and the magnetization history of the specific magnet.

The application engineer must define stability requirements by considering what changes can be tolerated. This can ultimately be done only by setting limits on specific device performance parameters over the lifetime of the device. However, magnet producers and testing laboratories trying to guide the user by characterizing magnet stability in a more general way must work with a few selected parameters tied to material and test-sample size, shape or operating permeance. For this purpose, a number of commonly used

design-related quantities are selected and "losses" defined as a percentage change from their initial values. The initial reference state can be "as-magnetized" (which can be done in different ways), or "prestabilized" (by heating after charging or by partial demagnetizing, a "knockdown"); it must be clearly defined. The nature of any adverse environmental influence must also be defined, and so must the time and frequency of exposure.

In the following it shall be assumed that for the specific device use under consideration the environment, temperature and time of exposure are those defined above in Item C, and that the losses are the cumulative changes over the stated lifetime of the device. As examples for measurements of stability, please consider the following "loss" definitions:

- a. Tolerable loss of the B-flux at a defined operating permeance or  $B_d$ -level.
- b. Tolerable loss of magnetic moment or average magnetization intensity ( $B-H$ ,  $M$ ,  $J$ ) at a specified highest demagnetizing field temporarily seen by the magnet in operation.
- c. Tolerable loss of the (normal) coercive force,  $B_H C$ .

For thermal exposure it is common practice to distinguish between "irreversible losses" incurred during short-time exposure (perhaps 1/2 to 4 hours of heating) and long-term "aging losses." For the present purpose, please consider only the long-term "aging loss" changes away from an initial state of the magnet that is achieved by whatever stabilizing treatment is deemed necessary. It is assumed that you specify such pre-treatment when you buy the magnet and that the "Required PM Properties" given in Item D above are for the pre-stabilized state.

Since the entire subject of stability is so complex, and it is difficult to define generally useful quantities to describe it, we request that you give your own definitions and a discussion if you feel that the above descriptions of stability are inadequate for your device requirements.